BROWN

The CMS Tracker

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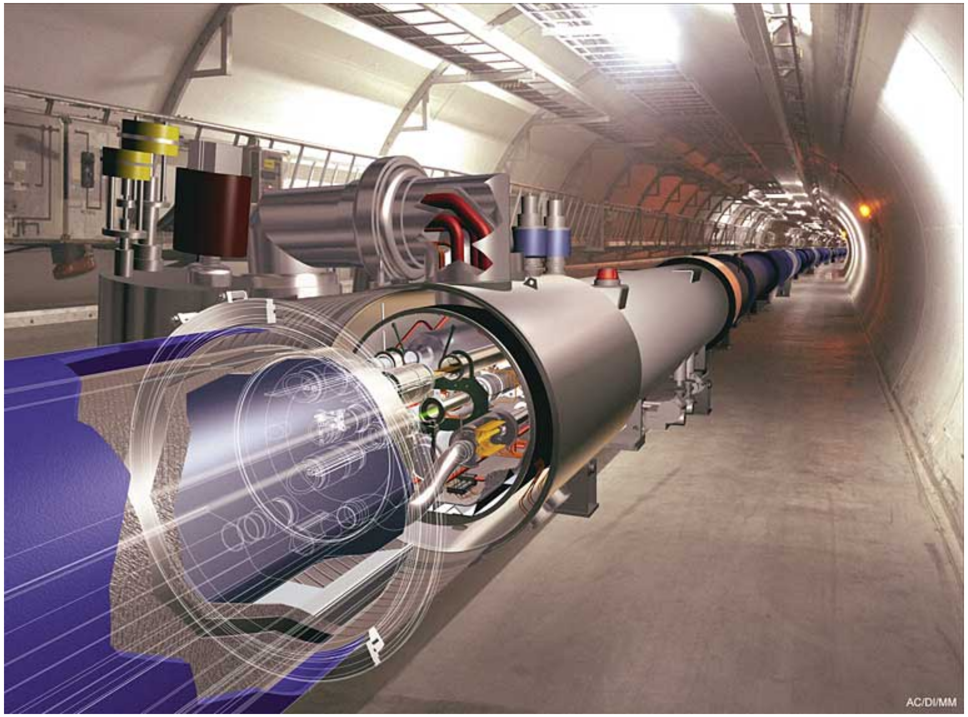
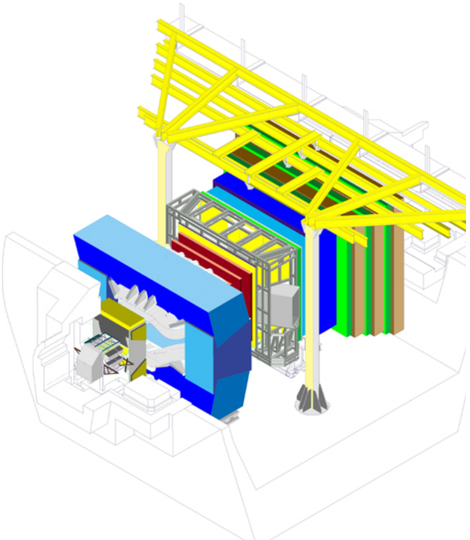
Outline

The CMS Tracker
Track reconstruction
Vertex reconstruction
b-tagging

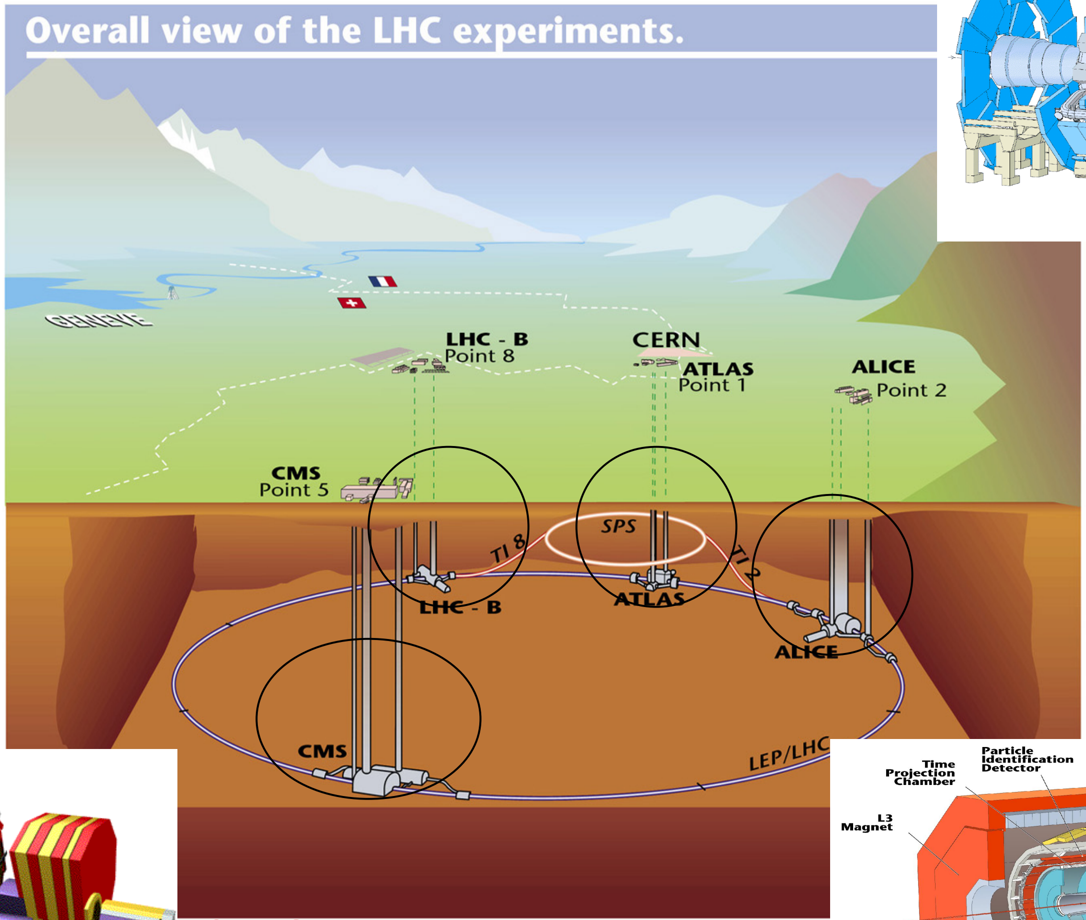
The LHC

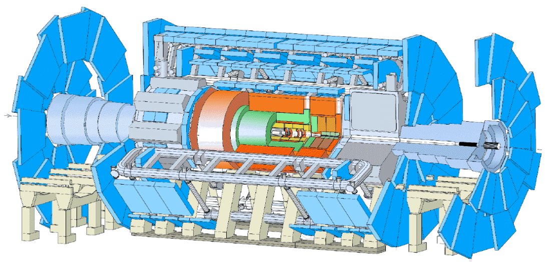
- LHC: proton-proton collisions at $\sqrt{s}$ = 14 TeV
  - 2010-2011: collisions at $\sqrt{s}$ = 7 TeV
- Design luminosity: 10^{34} cm^{-2} s^{-1} (~100 fb^{-1} per year)
  - 2010-2011: expect ~1 fb^{-1}
- Four experiments:
  - ALTAS, CMS: multi-purpose experiments, with emphasis in high-p_T physics
  - LHCb: experiment dedicated to B-physics
  - ALICE: Heavy ion experiment



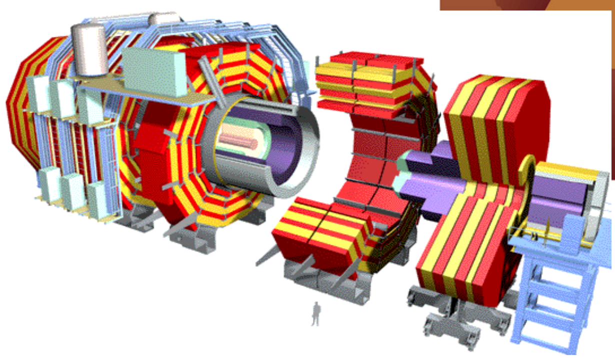


LHC-B

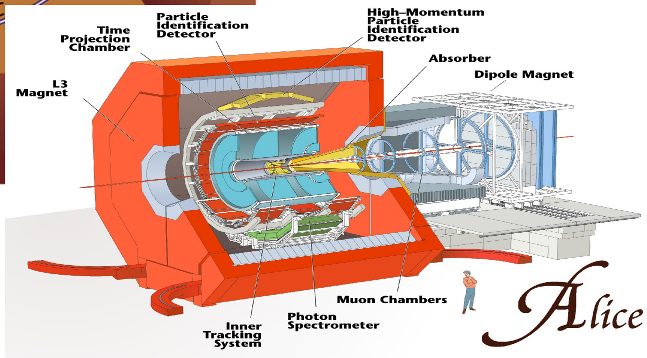




ATLAS

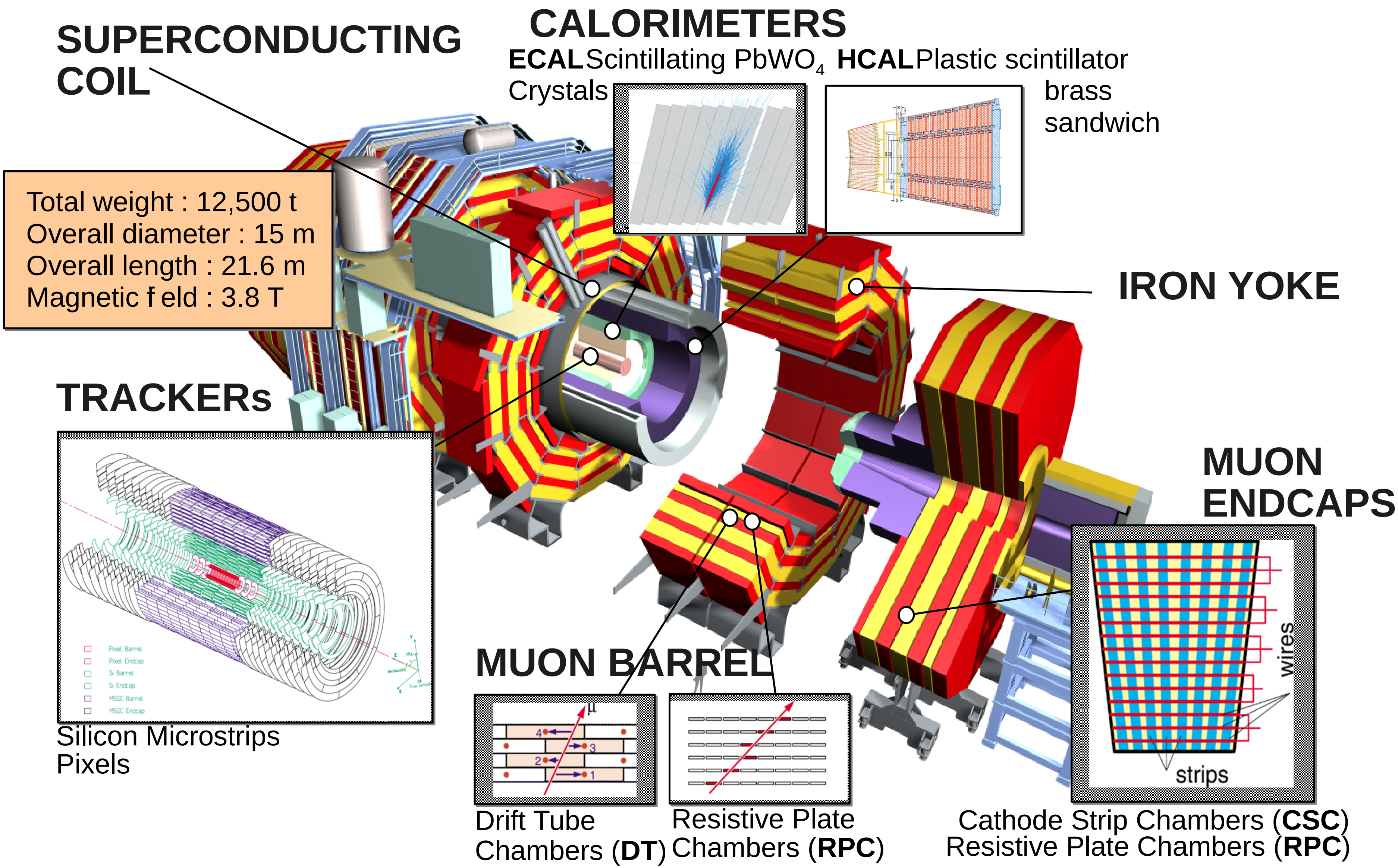


CMS



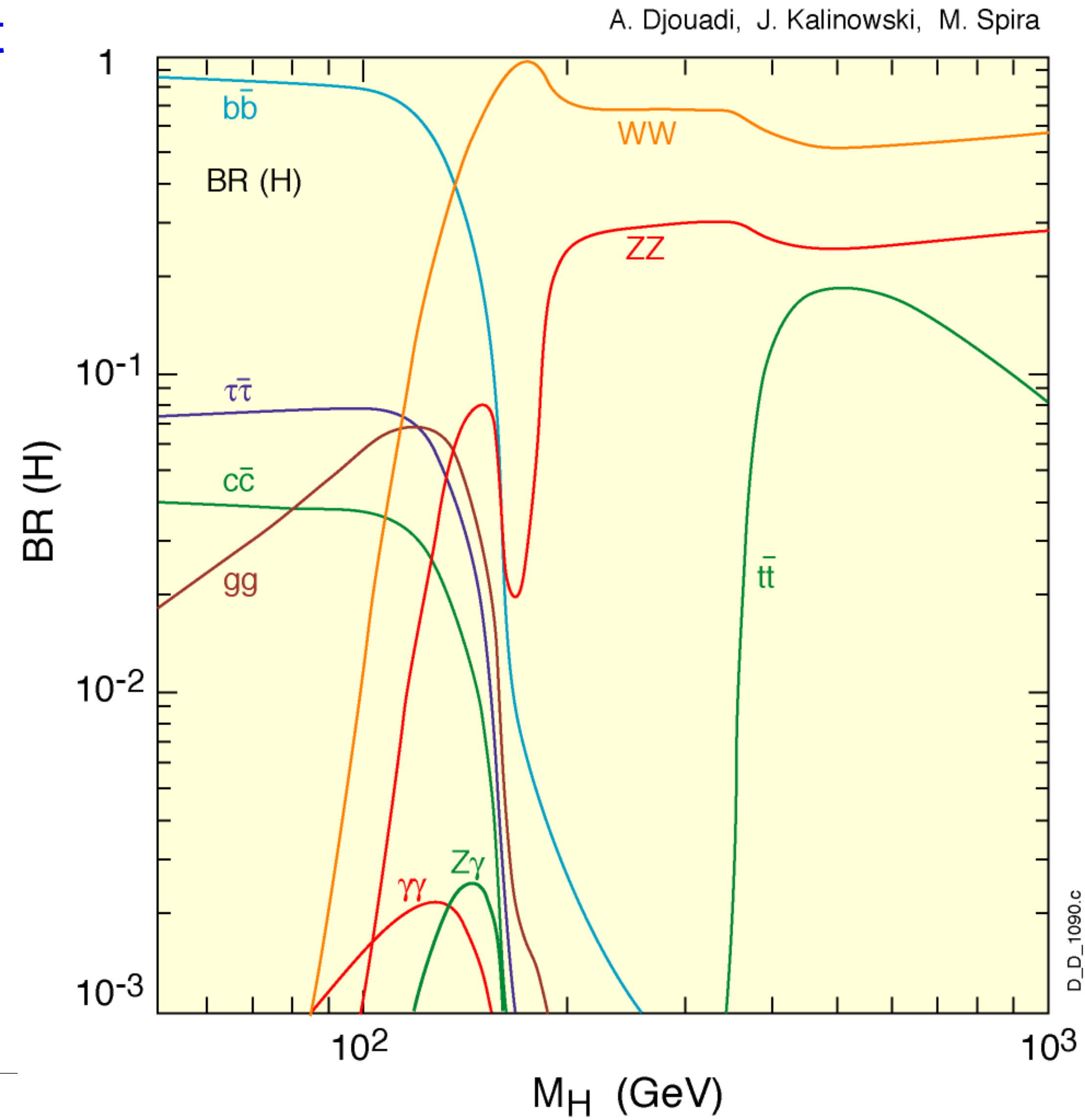
ALICE

The CMS experiment



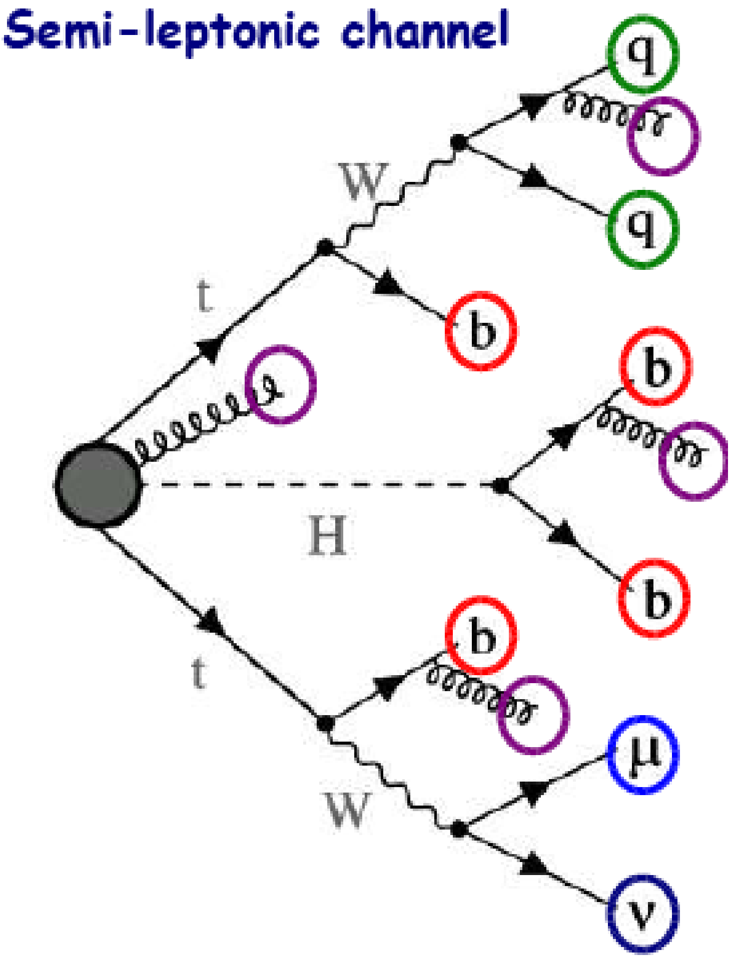
Introduction

- Many channels have *b*-jets in their final states (top, Higgs, SUSY)
  - efficient identification of jets originating from b-quarks
  - efficient rejection of non-*b* jets (=*u/d/s/g/c*)
- Example: Higgs boson decay at lower masses:
  - $H^0 \to b\bar{b}$: dominating
  - $H^0 \to \tau^+\tau^-$: BF ~8%
  - $H^0 \to ZZ^* \to l^+l^-l^+l^-$, $H^0 \to \gamma\gamma$: BF ~$1\text{-}3\cdot10^{-3}$

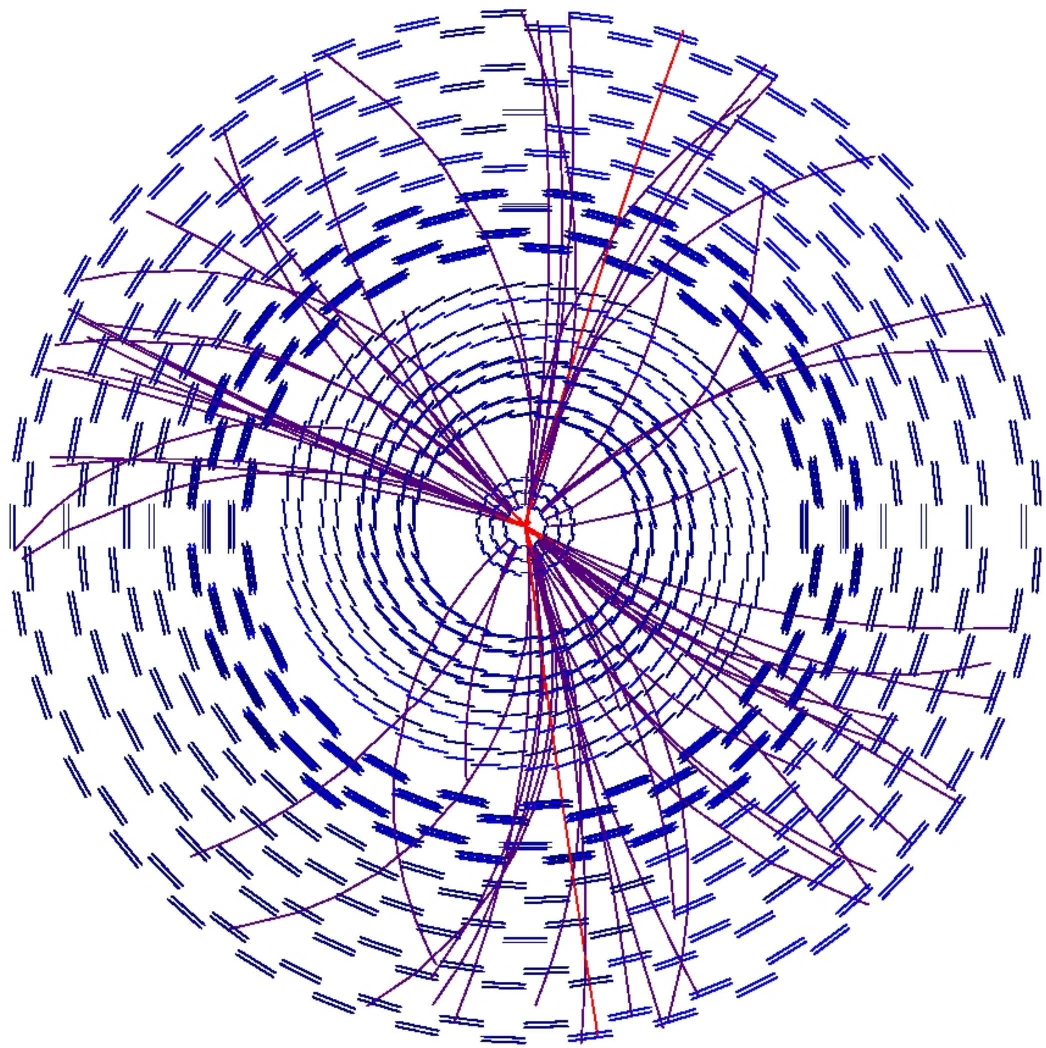


Higgs boson decay

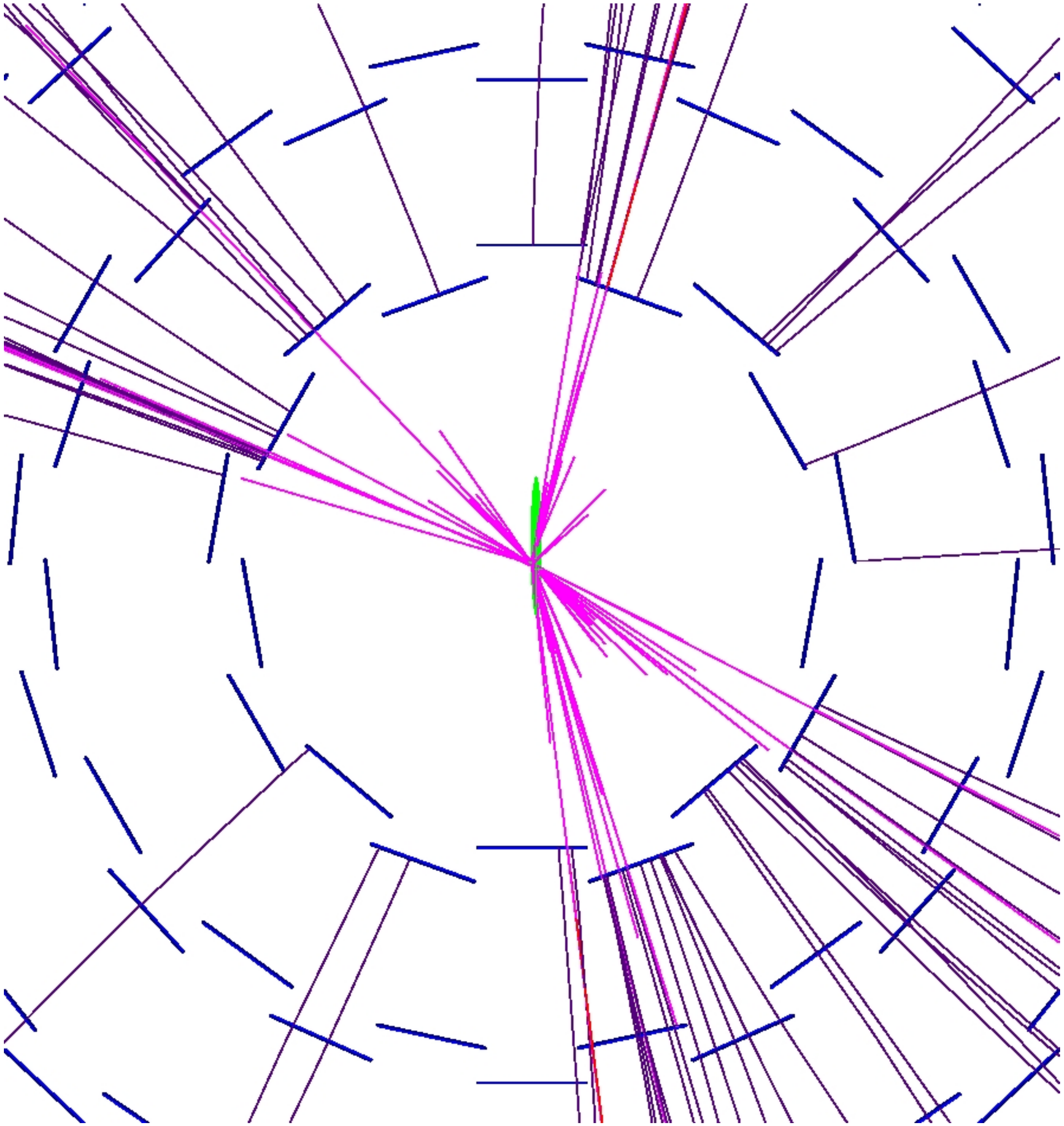
- Decay $H^0 \rightarrow bb$:
  - Complementary to $H \rightarrow \gamma\gamma$, measurement of the top-Higgs Yukawa coupling
- Search for associated production $t\bar{t}H$
  - 4 b jets from top and Higgs decay
  - W decay:
    - Leptonic decay: Isolated lepton (e or μ) + Missing E_T
    - Hadronic decay: 2 light jets
  - Additional jets from gluon radiations



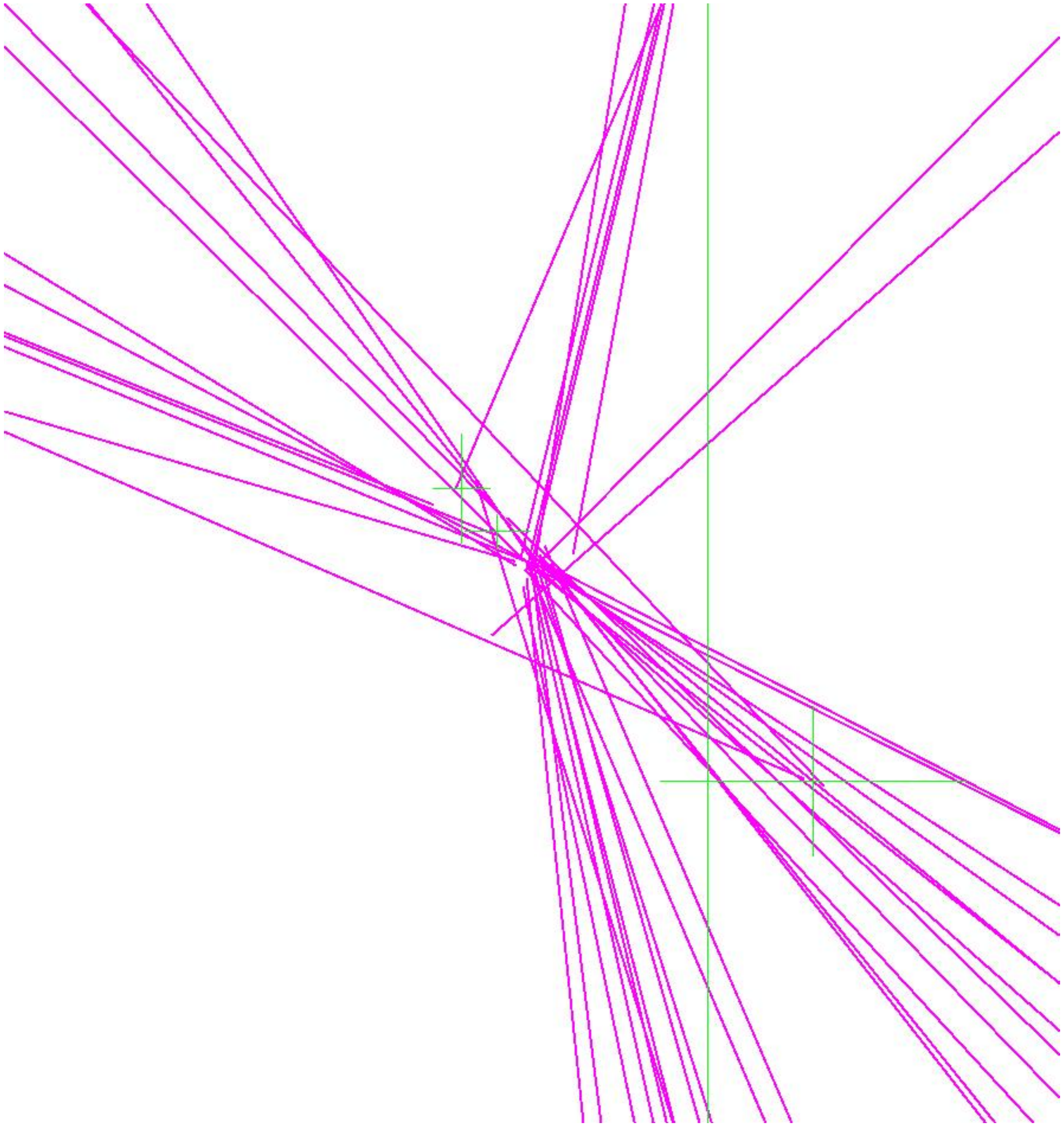
Higgs boson decay



Higgs boson decay



Higgs boson decay



SUSY searches

- SUSY: Decay chains with *b* quarks
  - stop searches: $\widetilde{q} \to q\widetilde{g},\ \widetilde{q} \to q\widetilde{\chi}_i^0,\ \widetilde{q} \to q'\widetilde{\chi}_i^{\pm},\ \ldots$
    - very often the lightest squark
    - Decays to *t* + neutralino or *b* + chargino
  - sbottom searches:
    - Decays to *b* + neutralino , *t* + chargino, or stop + *W*
  - gluino searches:
    - Often decay to *bb, tt* dominant

$$\widetilde{g} \to \bar{t}\widetilde{t}_1,\ \widetilde{t}_1 \to t\widetilde{\chi}_2^0,\ \widetilde{\chi}_2^0 \to l^+l^-\widetilde{\chi}_1^0$$

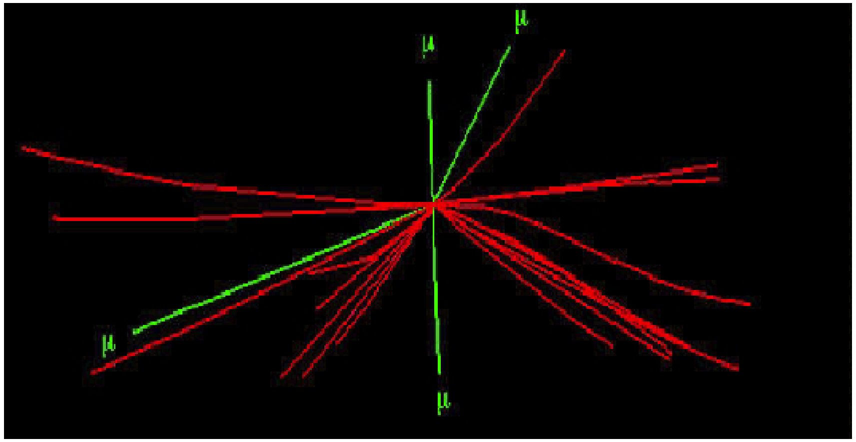
$$\widetilde{g} \to \bar{b}\widetilde{b}_1,\ \widetilde{b}_1 \to b\widetilde{\chi}_2^0,\ \widetilde{\chi}_2^0 \to l^+l^-\widetilde{\chi}_1^0$$

  - H^0 MSSM Higgs bosons: decay mostly via bb, *$\tau^+\tau^-$, tt pairs*
    - *Search through associated production, e.g. bb(h/H/A), or SUSY decay chain:*

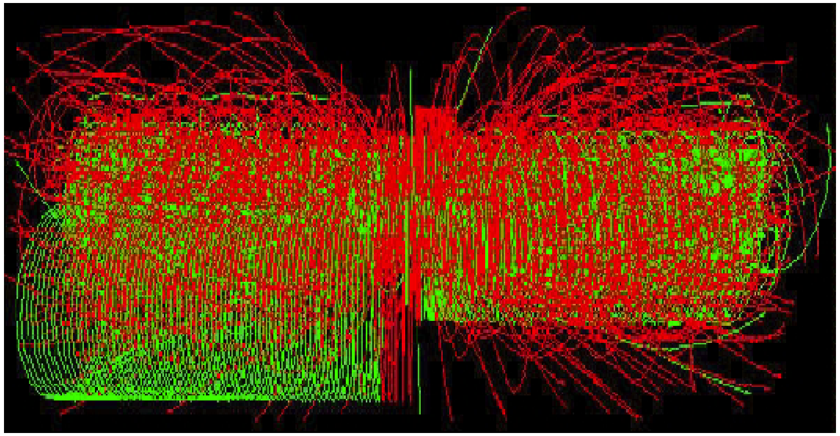
$$\widetilde{\chi}_2^0 \to h^0\widetilde{\chi}_1^0, h^0 \to b\bar{b}$$

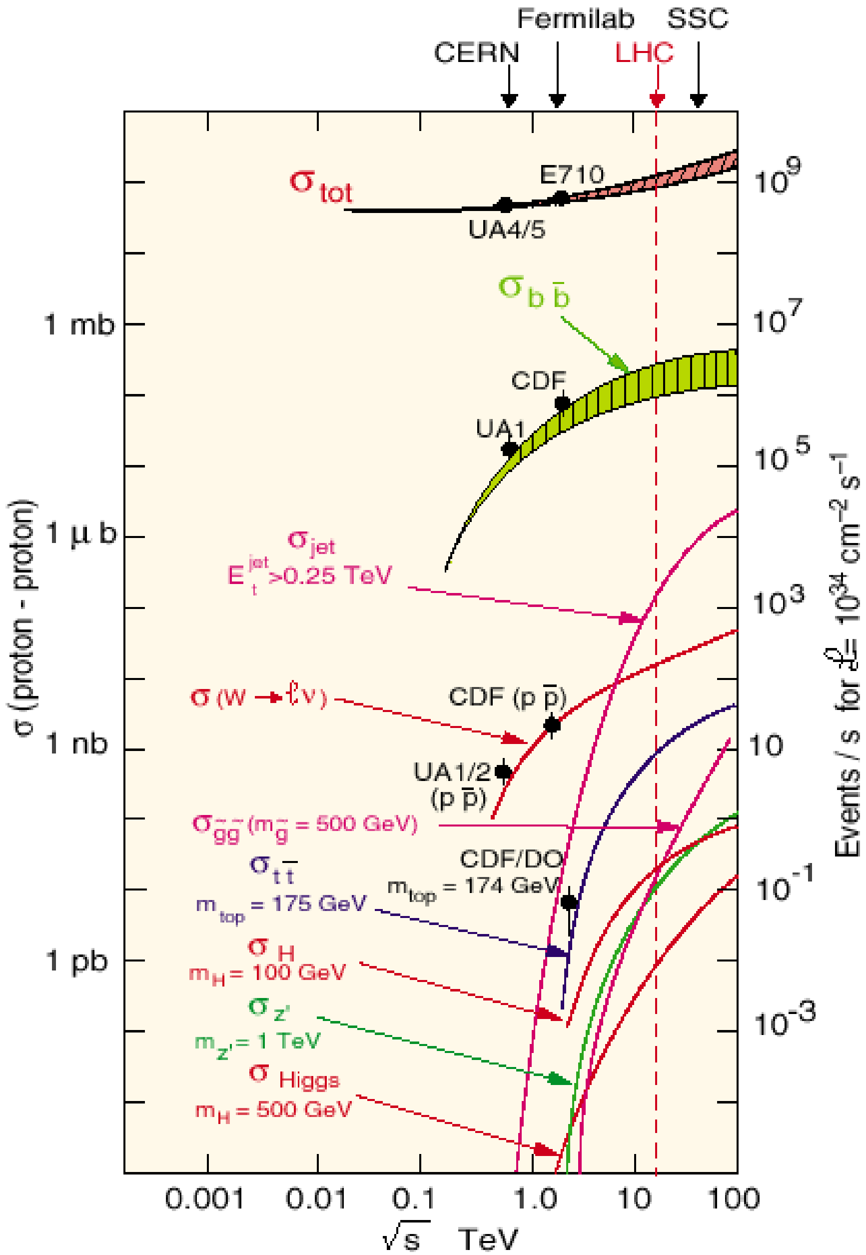
and then there is the pile-up...

One Higgs decay: $H \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$

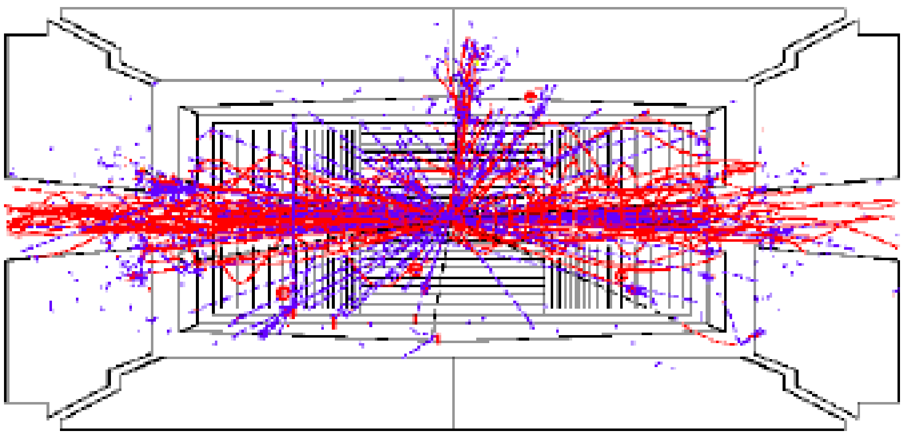


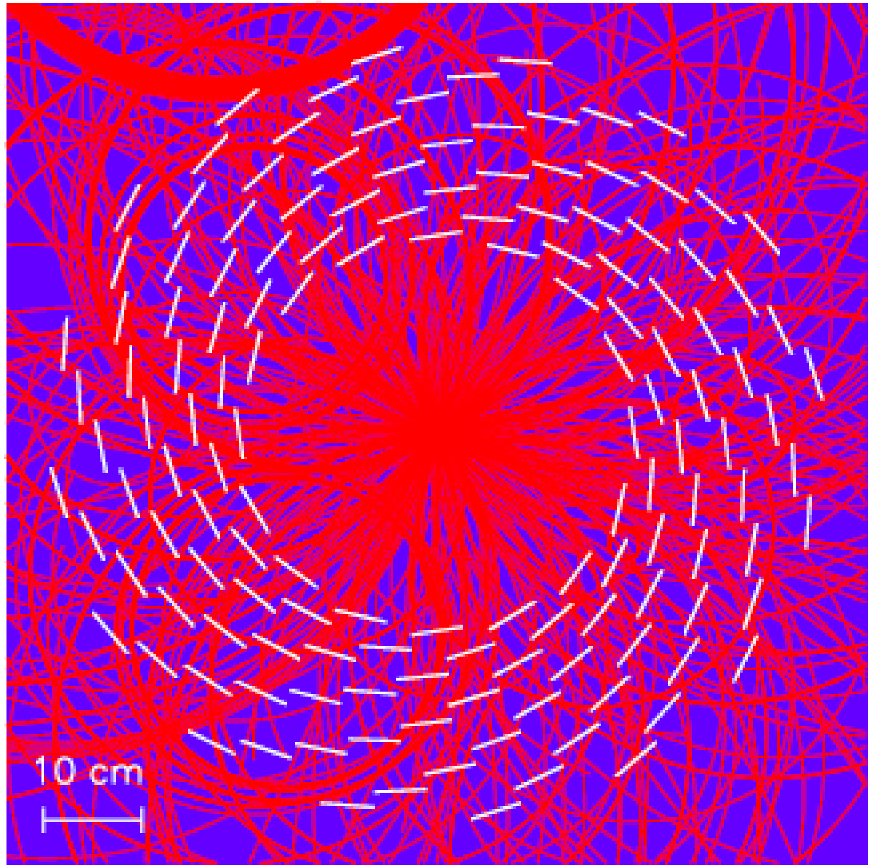
+ 25 minimum bias events (pile-up)....



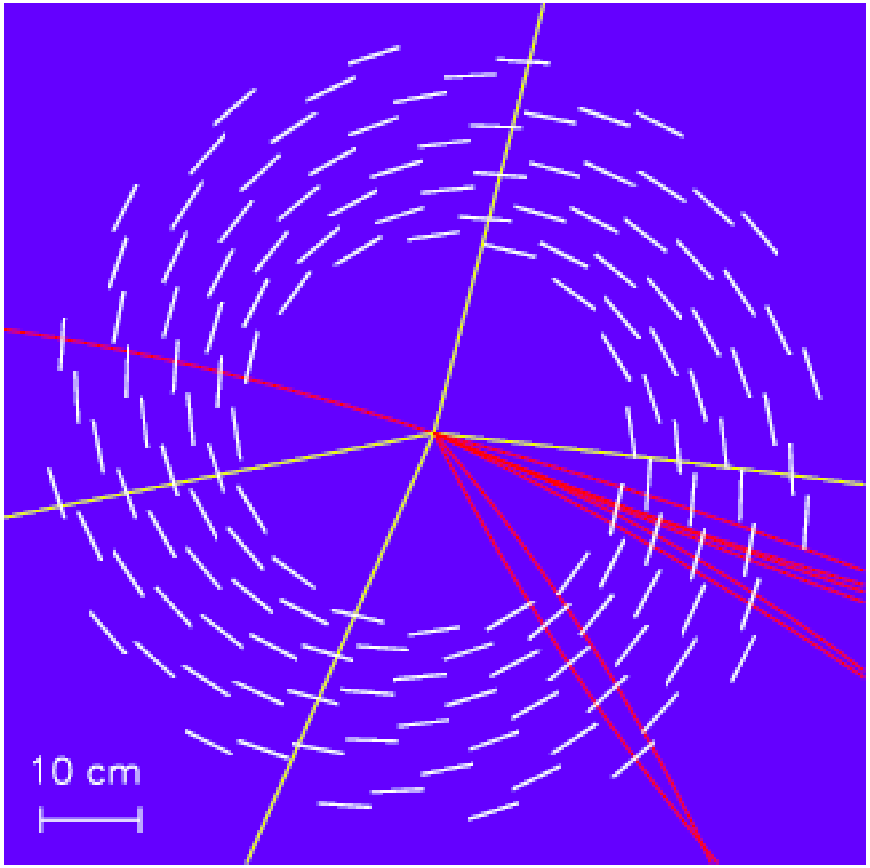


Higgs decay: $H \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$



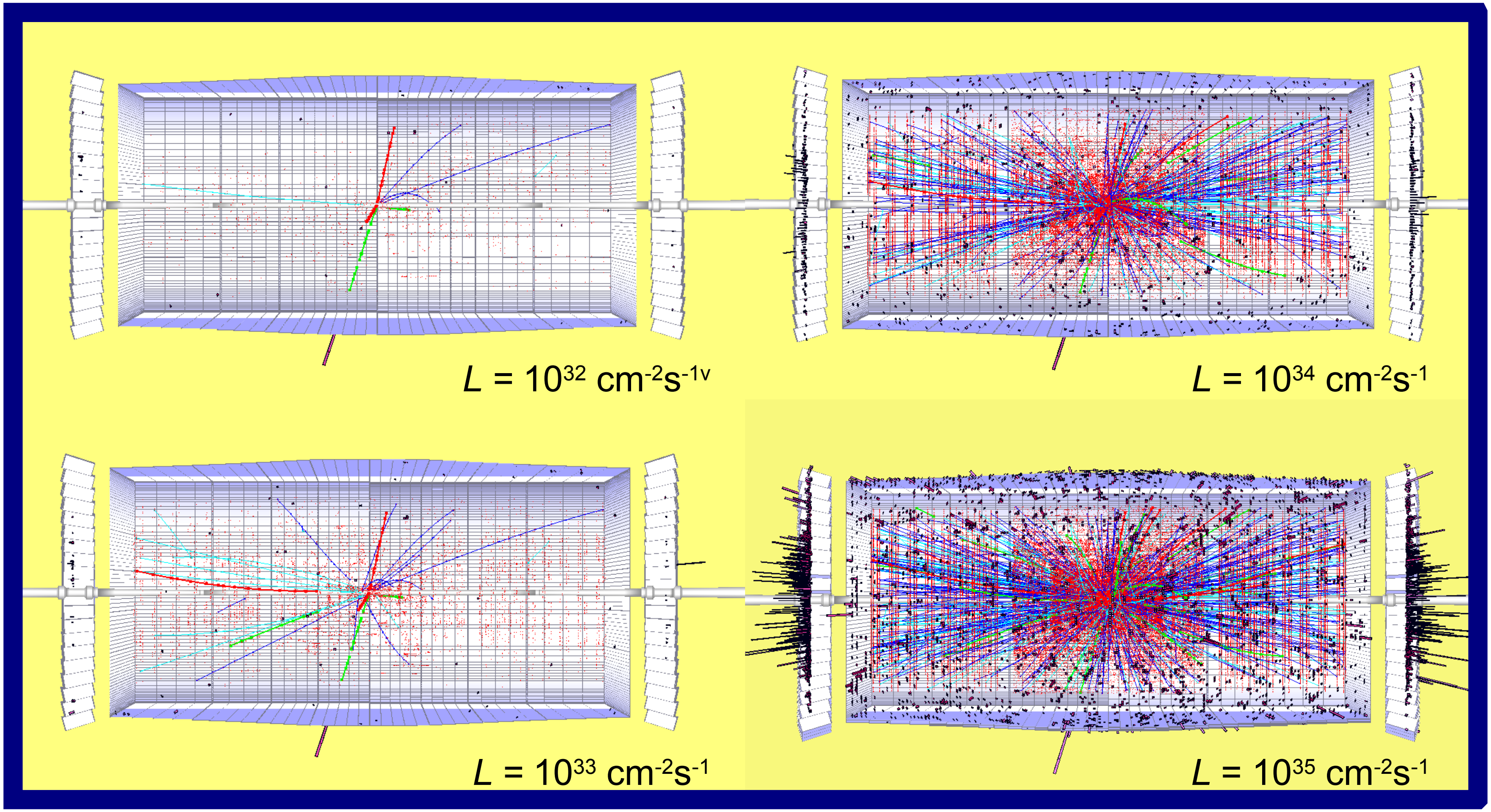


"Particles, particles, particles."



Tracks with p_T > 2 GeV/c

and then there is the pile-up...



Example of a 300 GeV/c^2 Higgs decay $H^0 \rightarrow Z^0\, Z^0 \rightarrow e^+e^-\mu^+\mu^-$
for luminosities between 10^{32} and 10^{35} cm^{-2}s^{-1}

Tracking at the LHC

- The LHC places severe requirements on the tracking detectors:
  - High bunch crossing rate: 40 MHz
  - High-luminosity: up to 10^{34} cm^{-2} s^{-1}
    - 25 inelastic collisions on average
    - >1000 charged tracks in the tracker

Tracking at the LHC

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  - High bunch crossing rate: 40 MHz
  - High-luminosity: up to 10^{34} cm^{-2} s^{-1}
    - 25 inelastic collisions on average
    - >1000 charged tracks in the tracker
- Requirements on the Tracker:
  - Fast response time to resolve bunch crossing (25 ns)
  - Fine granularity to resolve nearby tracks
  - High track and vertex reconstruction performance
    - Reconstruct narrow heavy objects: ~1-2% p_T resolution at ~100 GeV/c
    - Tag/reconstruct τ and *b*-jets through their secondary decays
  - Very high radiation environment:
    - Up to $3 \cdot 10^{14}$ $neq/cm^2/year$ at full luminosity in the innermost layers
    - To contain reverse annealing and limit leakage current, silicon detectors will operate at ~ -10° C
  - Limited material...

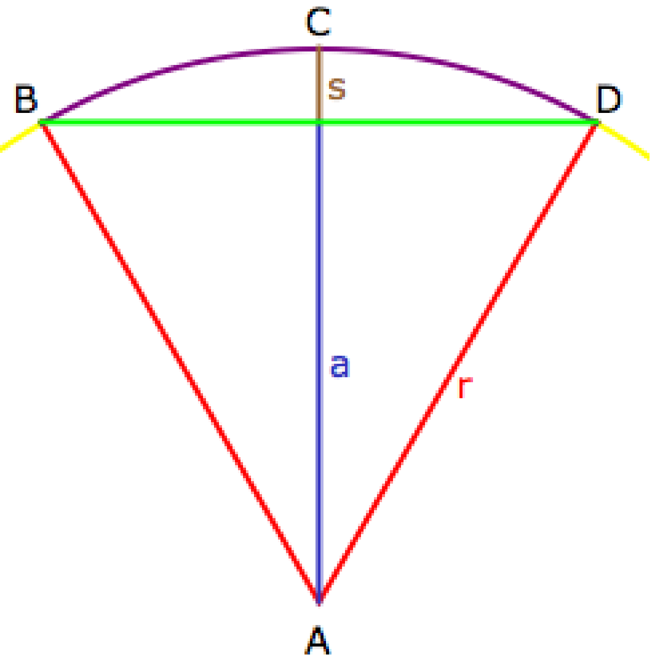
Momentum measurement

- Momentum measured by measuring curvature of track in magnetic field
- Deflection of charged particle in magnetic field:

$$p_T = |q| \cdot B \cdot r \qquad\qquad p_T\,(\mathrm{GeV}/c) = 0.3 \cdot |q| \cdot B \cdot r\,(\mathrm{Tm})$$

- Measurement of the sagitta:

$$s = r - r\cos(\theta/2)) = 2r\sin^2(\theta/4)$$



- For $\theta < 1$: $s = r\theta^2/8 = 0.3L^2B/(8p_T)$
- For CMS tracker, 1.1 m radius, 3.8 T:
  - 1.7 mm sagitta for 100 GeV/*c* p_T track!
  - p_T > 700 MeV/c to reach last layer
- With more than 10 measurements:

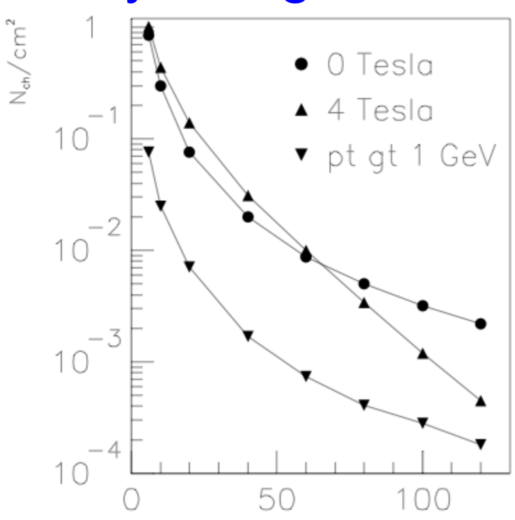
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x) \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

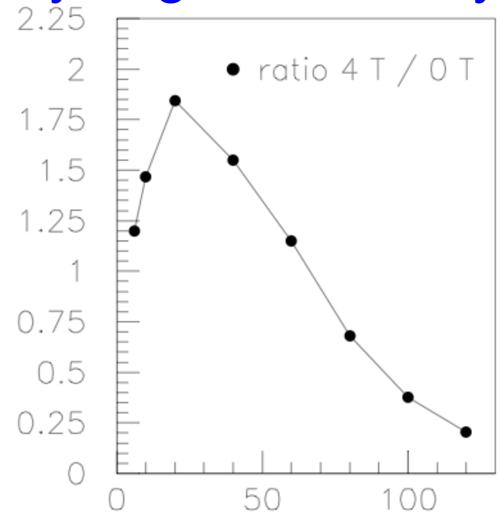
- But you have to add multiple scattering, energy loss, etc

See "Sagitta, Apothem, and Chord" from The Wolfram Demonstrations Project

Detector occupancy

- High track density at high luminosity: high hit density





Charged particle density per cm^2 at $\eta = 0$ for 20 minimum bias events

Ratio of hits at 4T / 0T

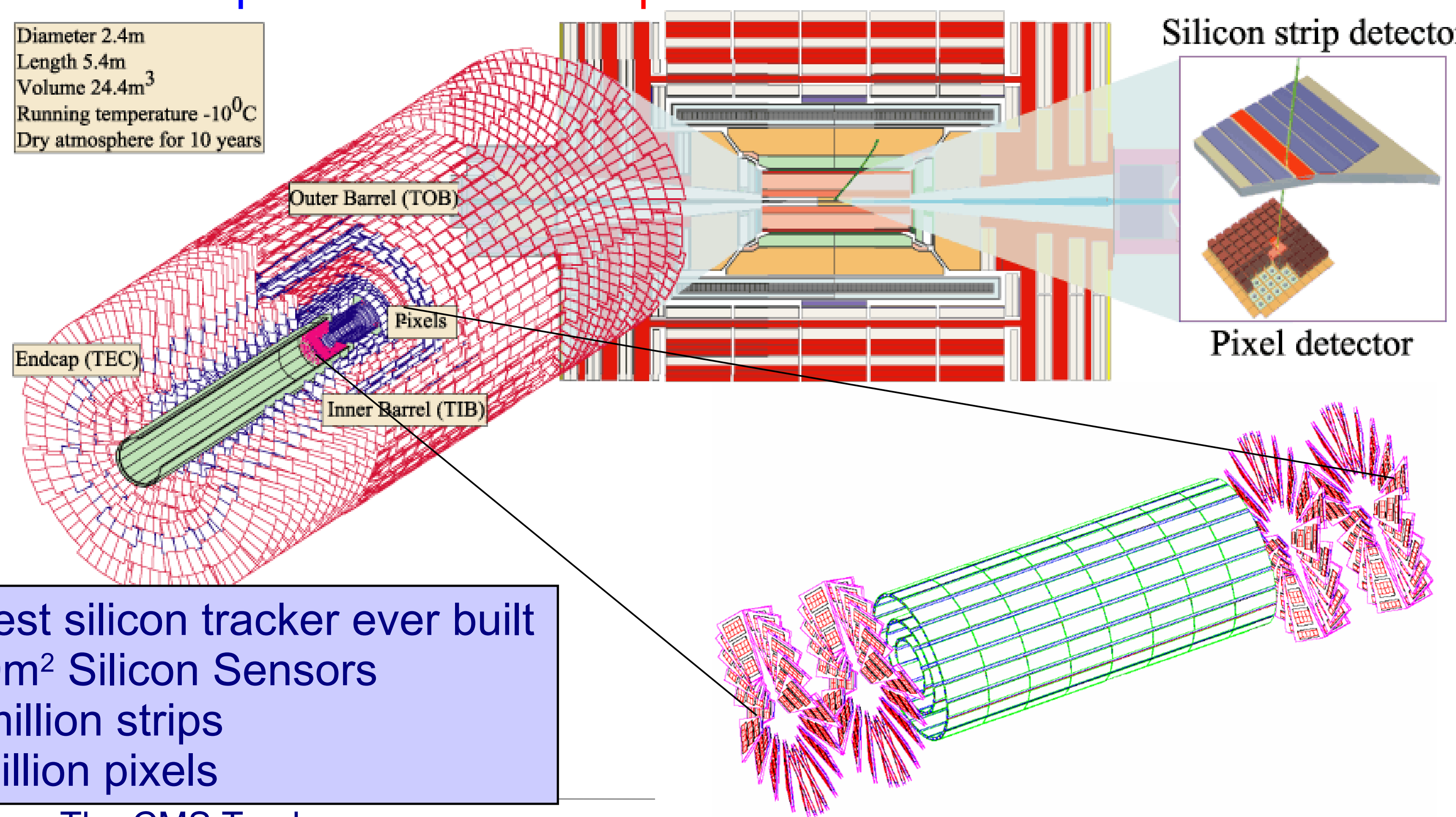
- Low occupancy (~few %) needed to resolve high track density
- Small cell size needed at low radius (well below 1 cm^2)
- Effect of magnetic field:
  - Low momentum tracks curl and do not reach outer layer of the tracker
  - Increases hit density in inner layers
  - Decreases in outer layer

The CMS tracker

➸ CMS has chosen an all-silicon configuration

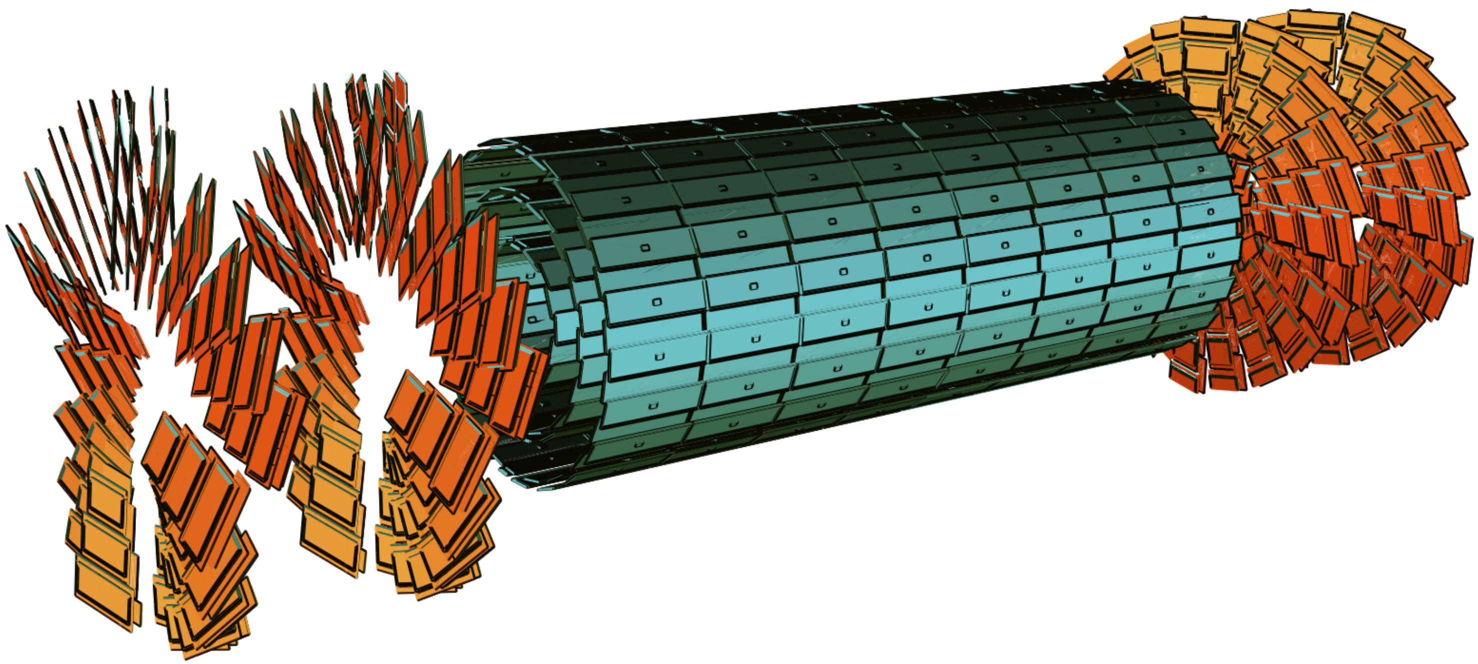
Rely on "few" measurement layers, each able to provide robust, clean and precise coordinate determination:

- Pixel detector: 2 - 3 points
- Silicon Strip Tracker: 10 - 14 points



Largest silicon tracker ever built
~200m^2 Silicon Sensors
9.3 million strips
66 million pixels

The Pixel detector



Geometry:

- 3 Barrel layers
  r = 4.3 cm, 7.2 cm, 11.0 cm
- 2 Pairs of Forward/Backward Disks
  r = 6 cm-15 cm ; z = 34.5cm, 46.5cm

Pixel-size: 100 μm x 150 μm

Hit-resolution:

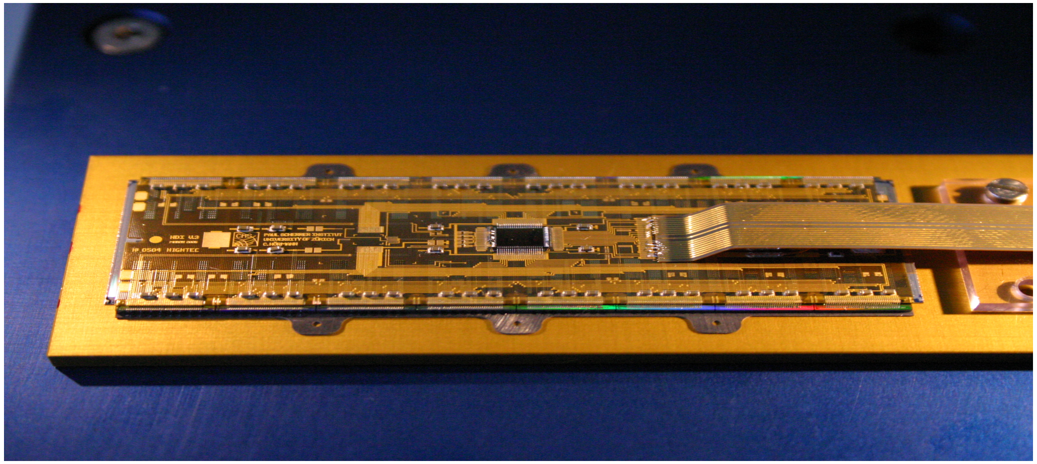
- r-ϕ : ~ 10 m
- r-z : ~ 20 m

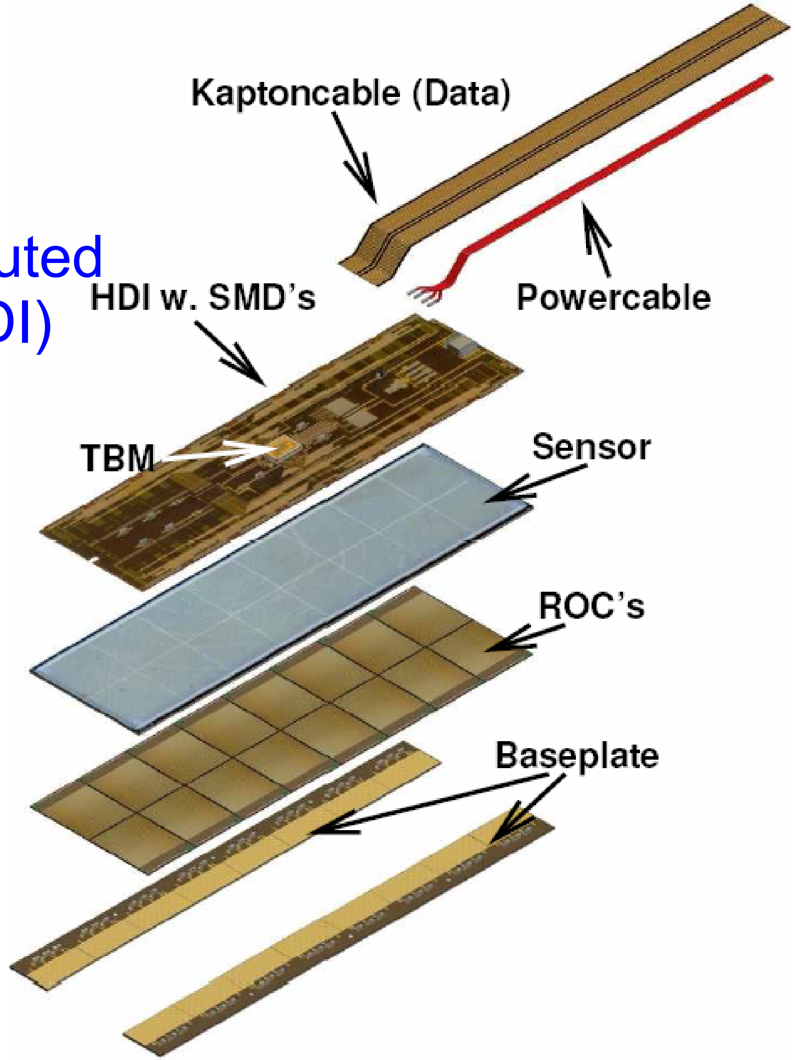
➼ 3 high resolution measurement points for $|\eta| < 2.2$

- Active area ~ 1m^2 - 66$\cdot$10^6 pixels
- 704 barrel modules, 96 barrel half modules, 672 endcap modules

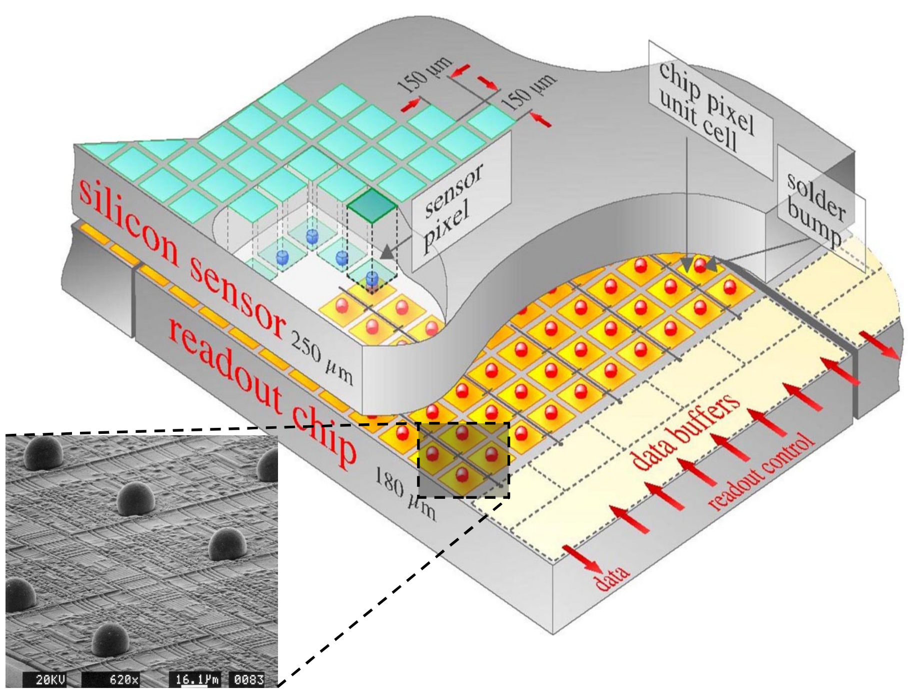
The Pixel module

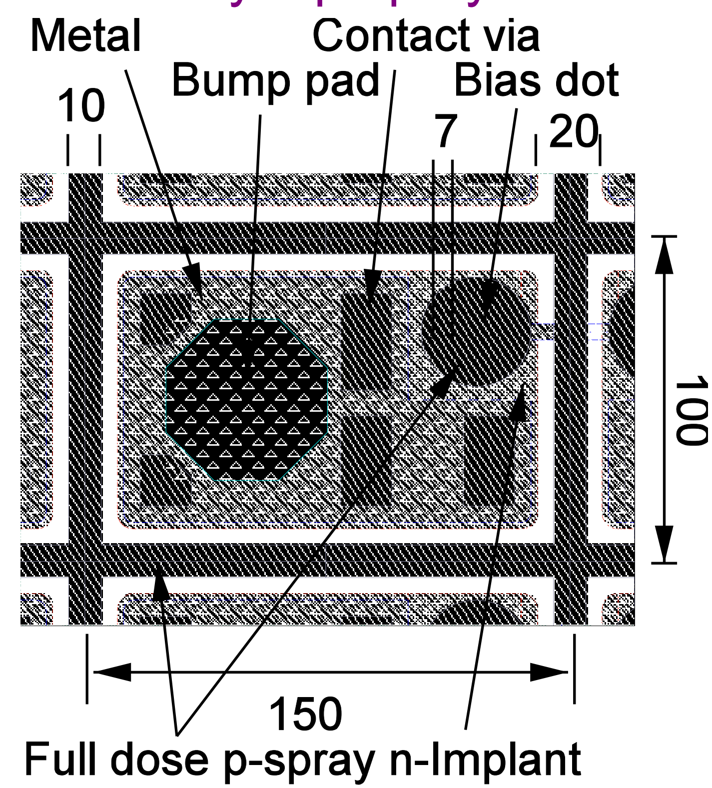
- 285 µm thick silicon sensor bump-bonded to front end chips (ROC)
- A barrel module contains a silicon sensor read out by sixteen front end chips
- Incoming and outgoing signals are distributed though a high density interconnection (HDI) covering the silicon sensor.
- A silicon base plate holds the module together





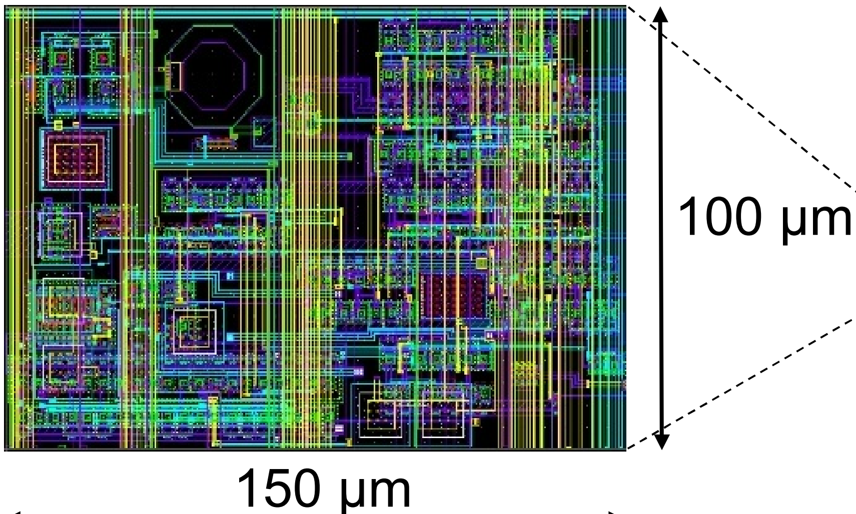
- The Pixel sensor cell:
  - Bump-bonded to front-end circuit via a 20 μm iridium bump
  - Implant covered with a metal layer to permit electrical contact with bump bonds
  - Bias dot connects the cell with other pixels to keep them at the same potential
  - n-doped silicon implant in a n-type bulk surrounded by a p-spray for isolation

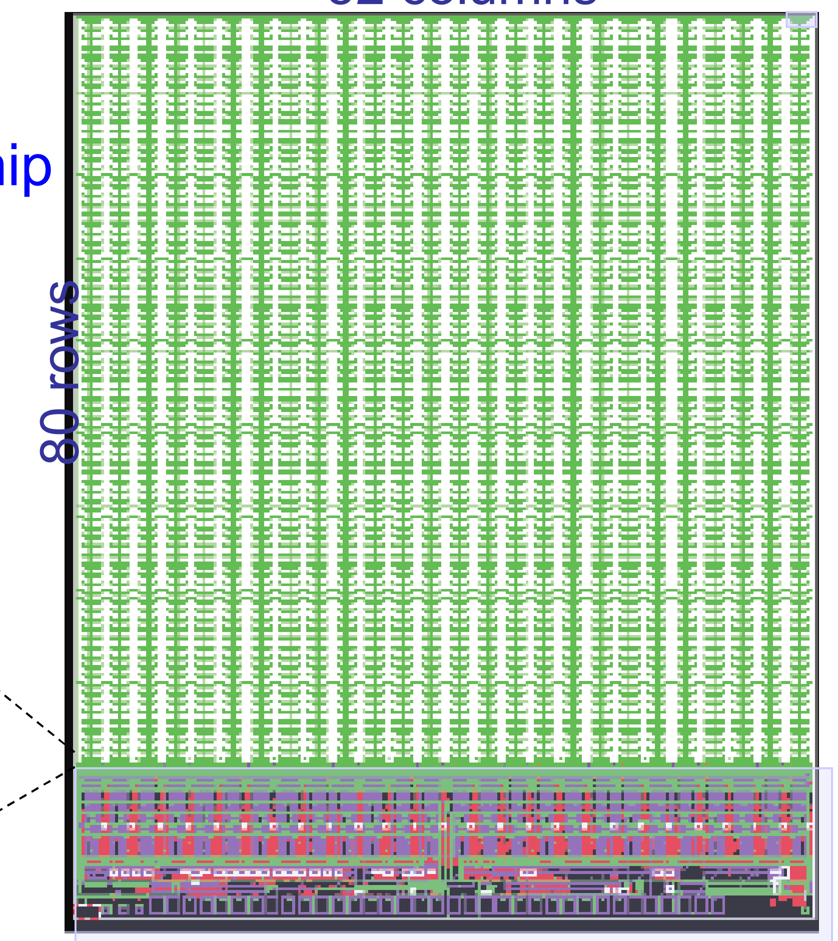




The Pixel readout chip

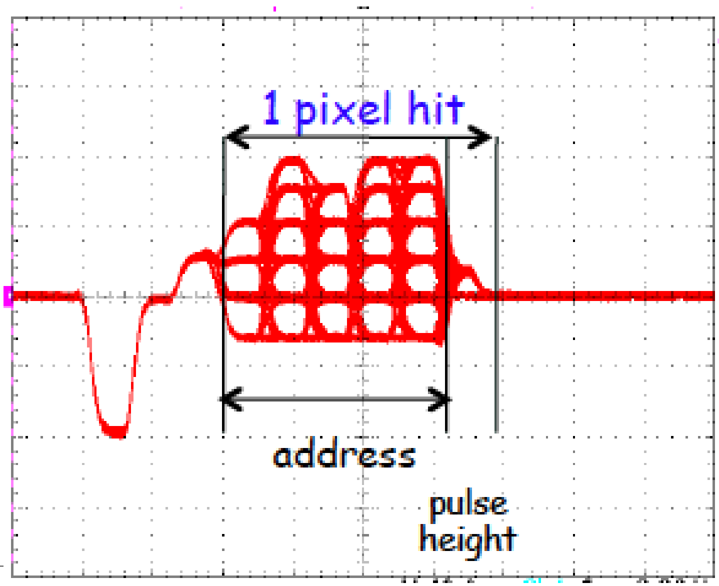
- Matrix of 52x80 readout cells with periphery at the bottom
- Each cell is composed of a charge amplifier, shaper, programmable discriminator and storage capacitor
- Only cells with a charge over a given threshold transfer the information to the chip periphery, together with time stamp and address
- The charge is read out only if the hit is validated by a L1 trigger

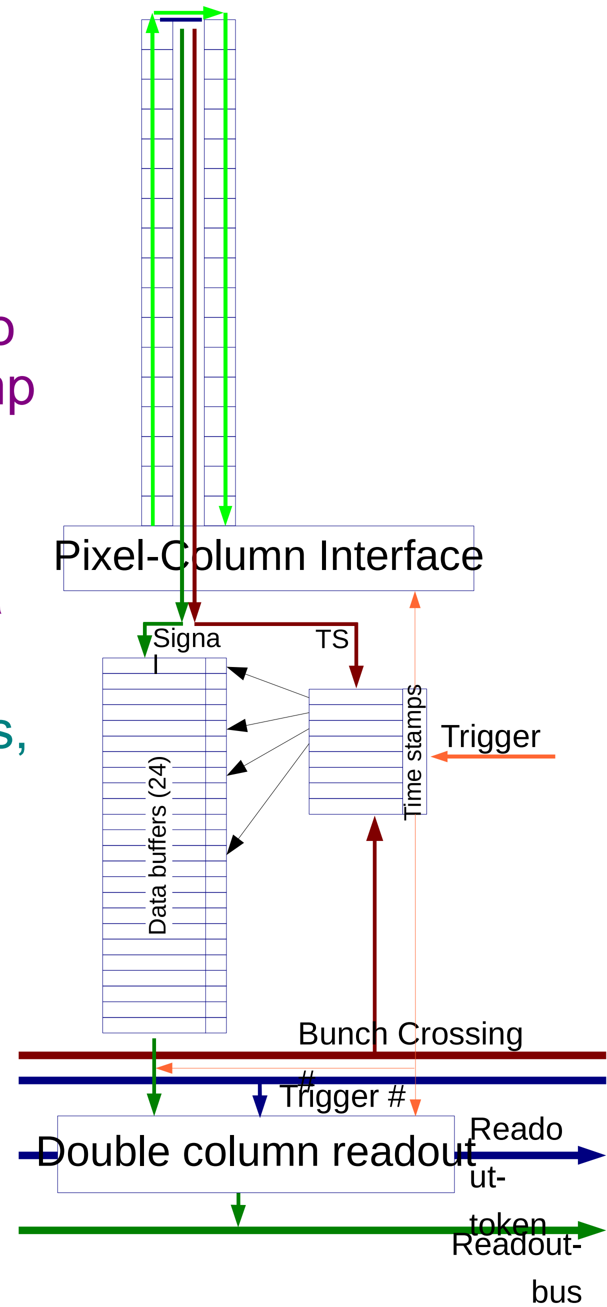




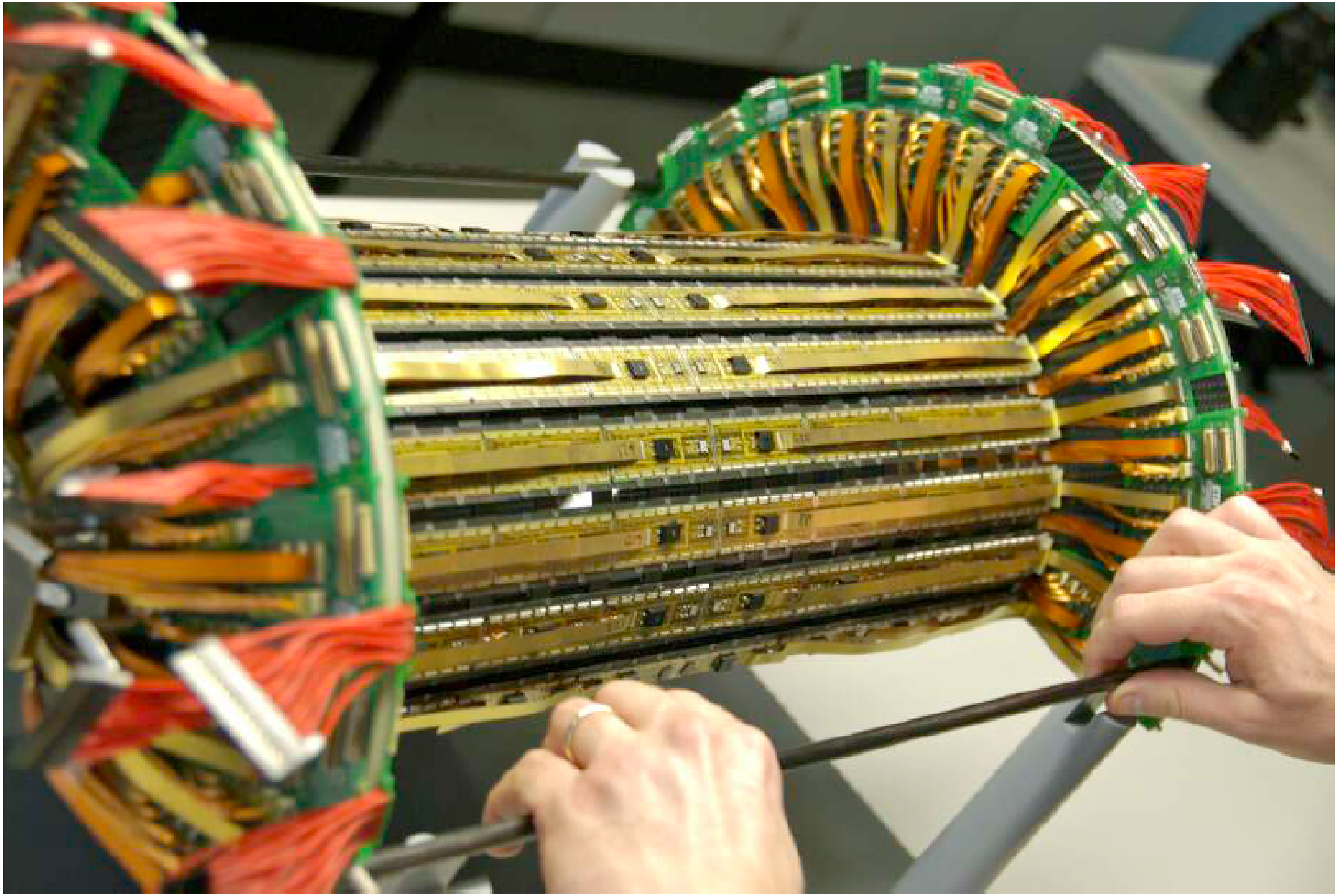
The Pixel readout chip

- Column Drain Architecture:
  - A pixel above threshold sends Fast Column Or to periphery
  - Periphery sets timestamp and initiates a token scan
  - Every hit pixel copies data within 2 bunch crossings to the periphery where the data is linked to the timestamp
  - If the hit is confirmed by a trigger, the double column activity stops and readout is prepared
  - With the corresponding token, the data is sent to data acquisition and the double column resets itself
    - 40 MHz Analog output: address encoding 5 clocks, charge 1 clock





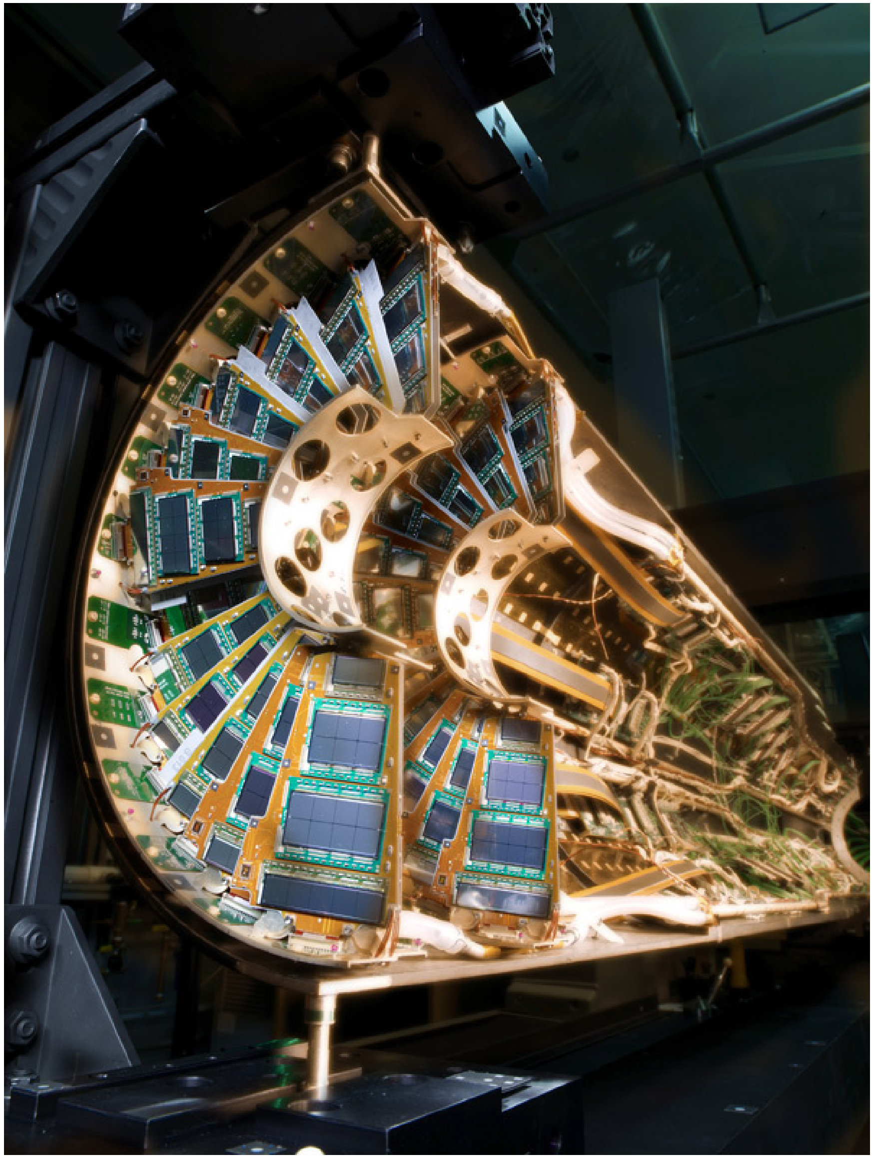
The Pixel Barrel



The Pixel Barrel

The Forward Pixel Disks

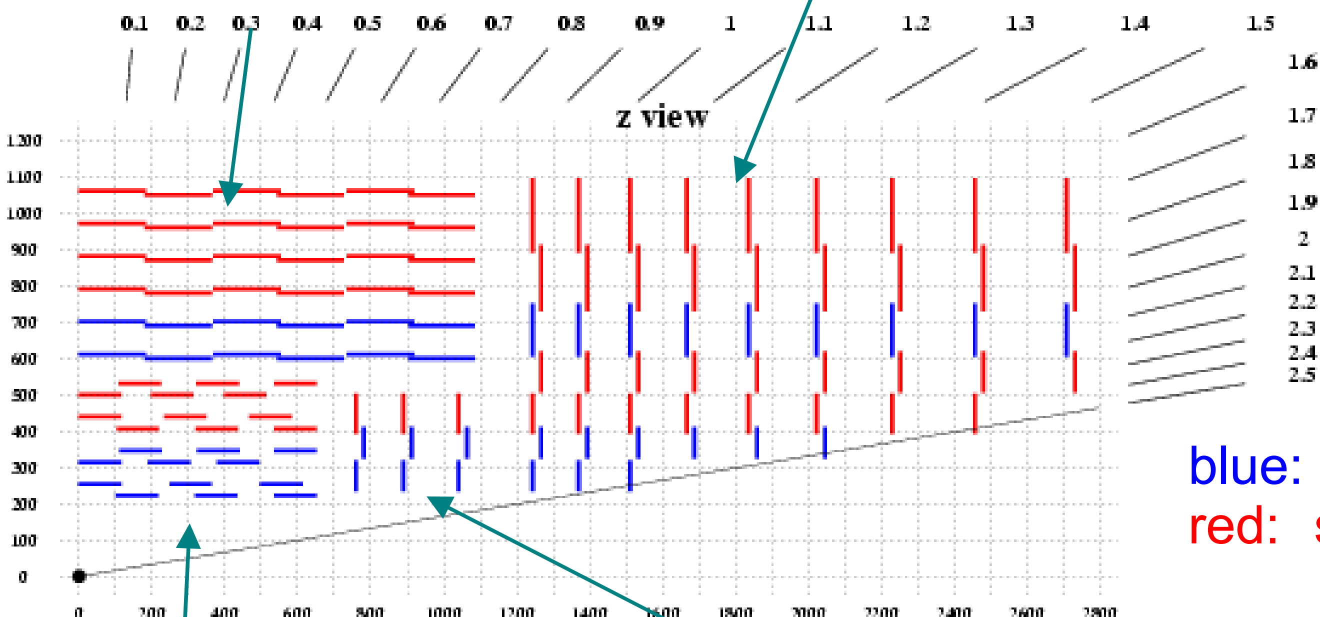
- Turbine disks consist of 24 blades
- Blades rotated by 20° for charge sharing:
  - Lorentz angle
  - Track inclination
- 7 detector modules per blade
  - 4 (3) on the front (back) side
- Modules of varying size, from 2 to 10 ROC.
  - 45 ROC per blade



The Silicon Strip Tracker

Outer Barrel (TOB): 6 layers
- Thick (500 μm) sensors
- Long Strips
- Rectangular sensors

Endcap (TEC): 9 disks pairs
- Trapezoidal sensors
- r<60cm: Thin sensors
- r>60cm: Thick sensors



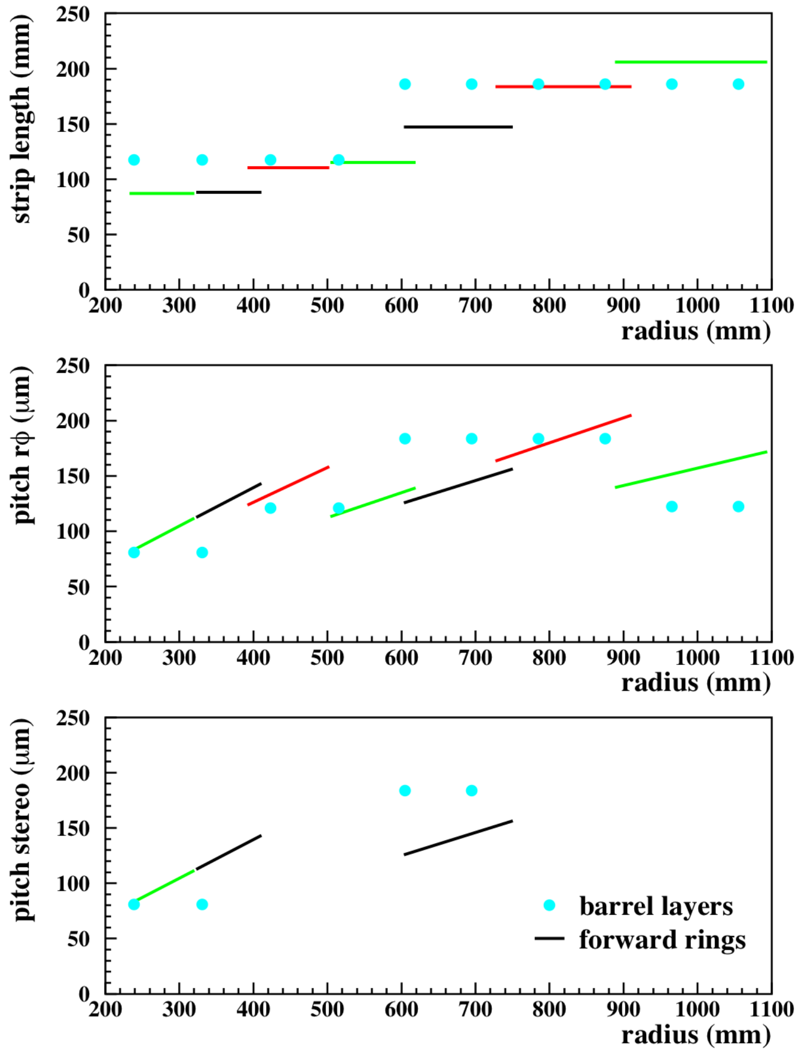
blue: double-sided detectors
red: single-sided detectors

Inner Disks (TID): 3 disks pairs
- Thin sensors
- Trapezoidal sensors

Inner Barrel (TIB): 4 layers
- Thin (320 μm)sensors
- Short Strips
- Rectangular sensors

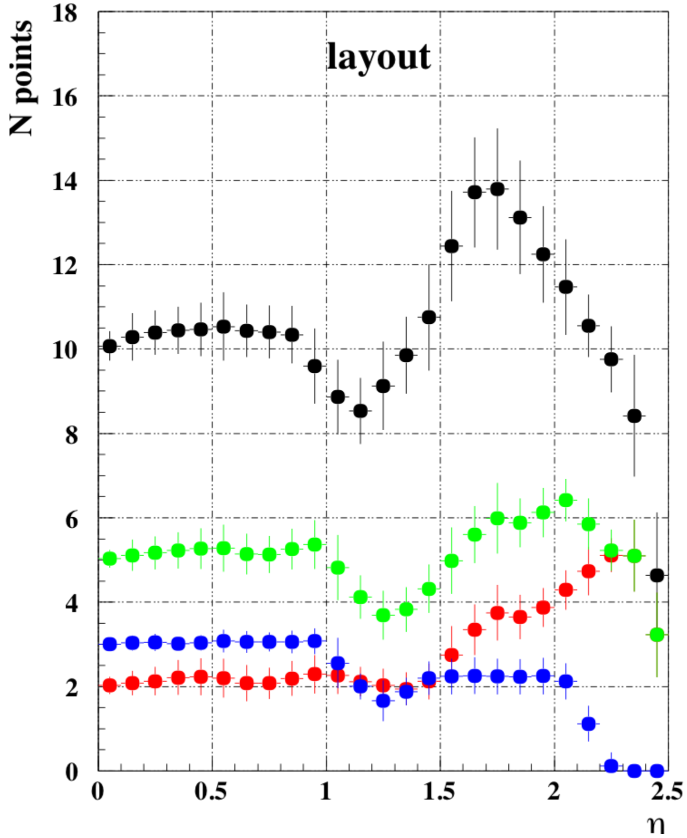
- 440 m^2 of silicon wafers
- 198 m^2 of silicon sensors
- 9'316'352 strips

The Silicon Strip Tracker



➸ 15 different sensor geometries

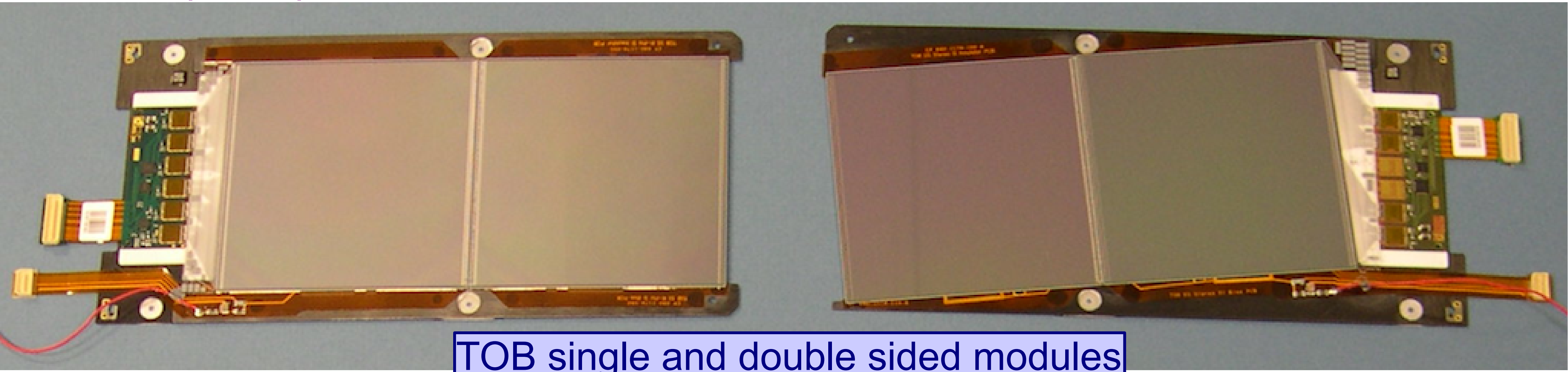
Number of SST hits by tracks:



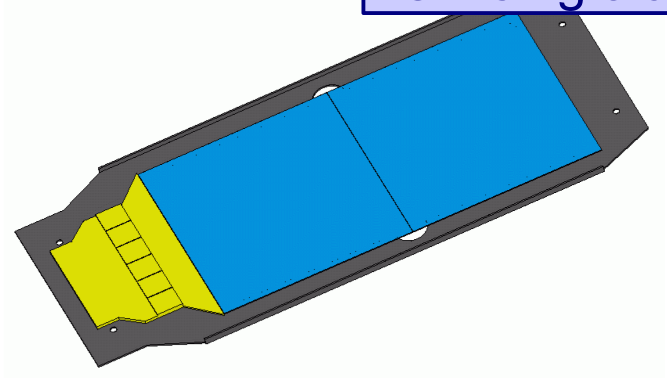
Black: Total number of hits
Green: double-sided hits
Red: double-sided hits in thin detectors
Blue: double sided hits in thick detectors.

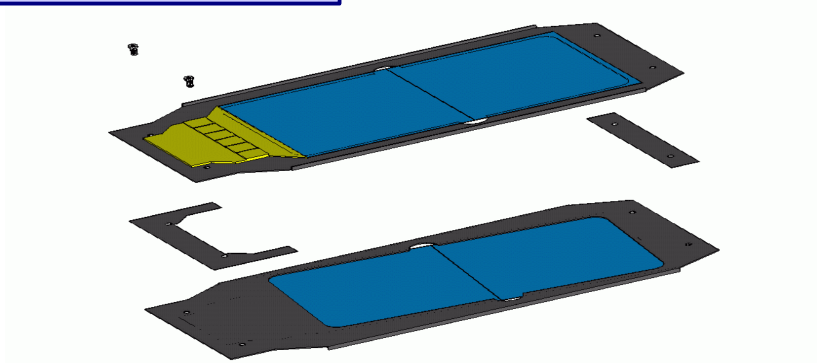
The Silicon Strip Tracker

- Single-sided sensors:
  - Double-Sided modules are made of two module of the same type glued back to back, tilted by 100 mrad
  - 6'136 thin (320 µm) sensors, 1 sensor per detector element
  - 18'192 thick (500 µm) sensors, 2 sensors per detector element
  - p+ strip on n bulk sensors

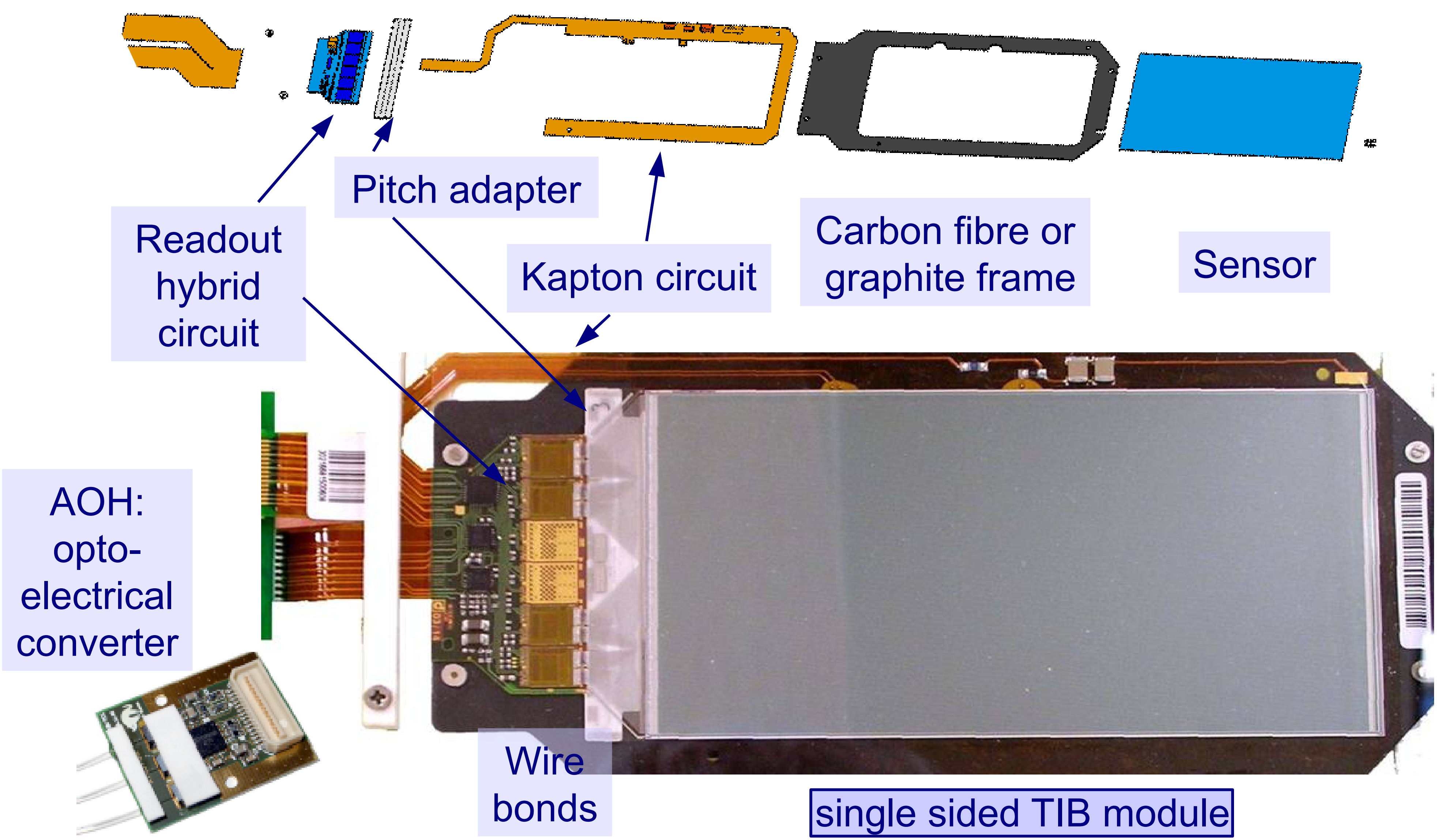


TOB single and double sided modules





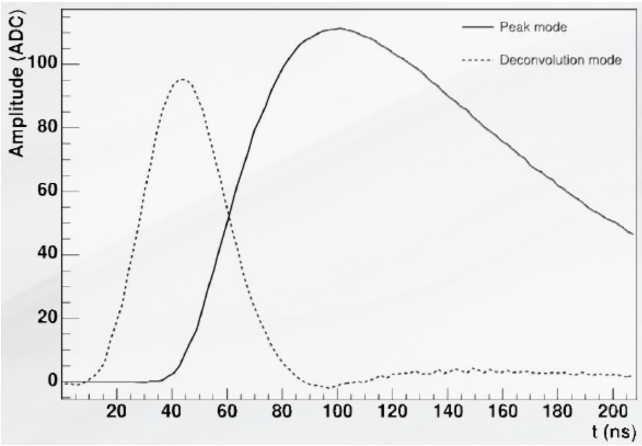
The module



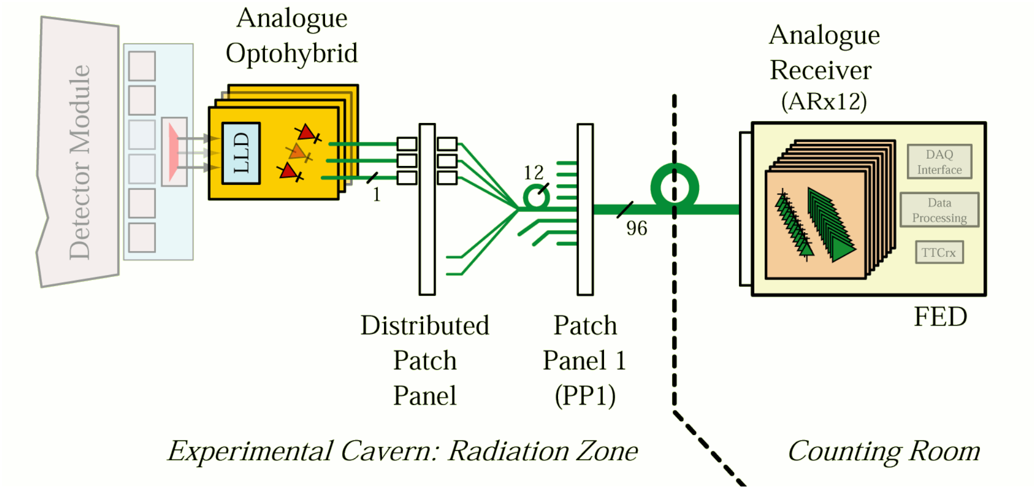
Pitch adapter
Readout hybrid circuit
Kapton circuit
Carbon fibre or graphite frame
Sensor
AOH: opto-electrical converter
Wire bonds
single sided TIB module

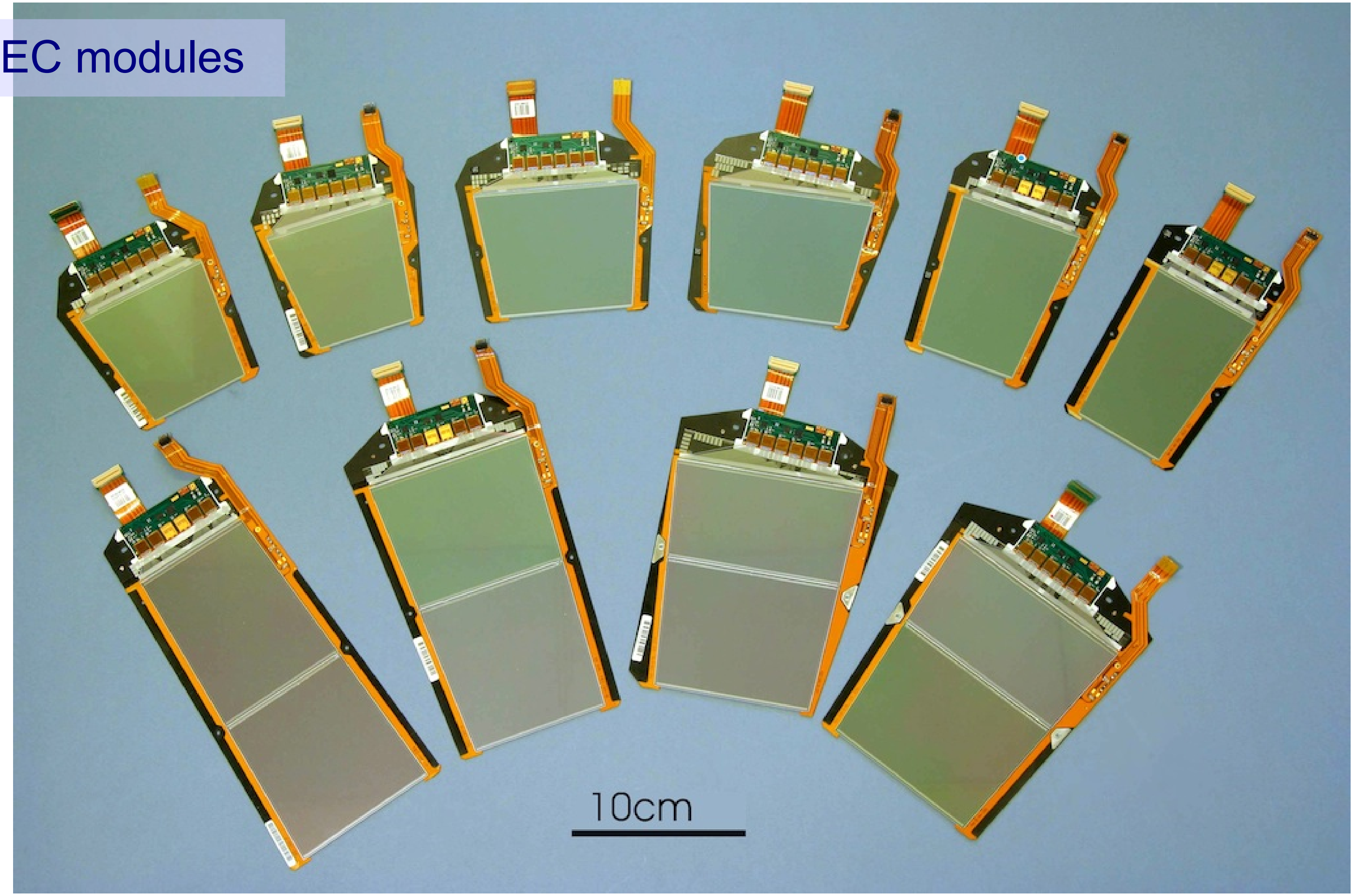
The readout and control systems

- Read-out system:
  - APV25 readout chip, with 128 channel
  - Sampling: Peak and deconvolution mode
    - Peak (75ns): debug and early commissioning
    - Deconvolution (25 ns): fast signal shaping, reduce pile-up of events, nominal operation

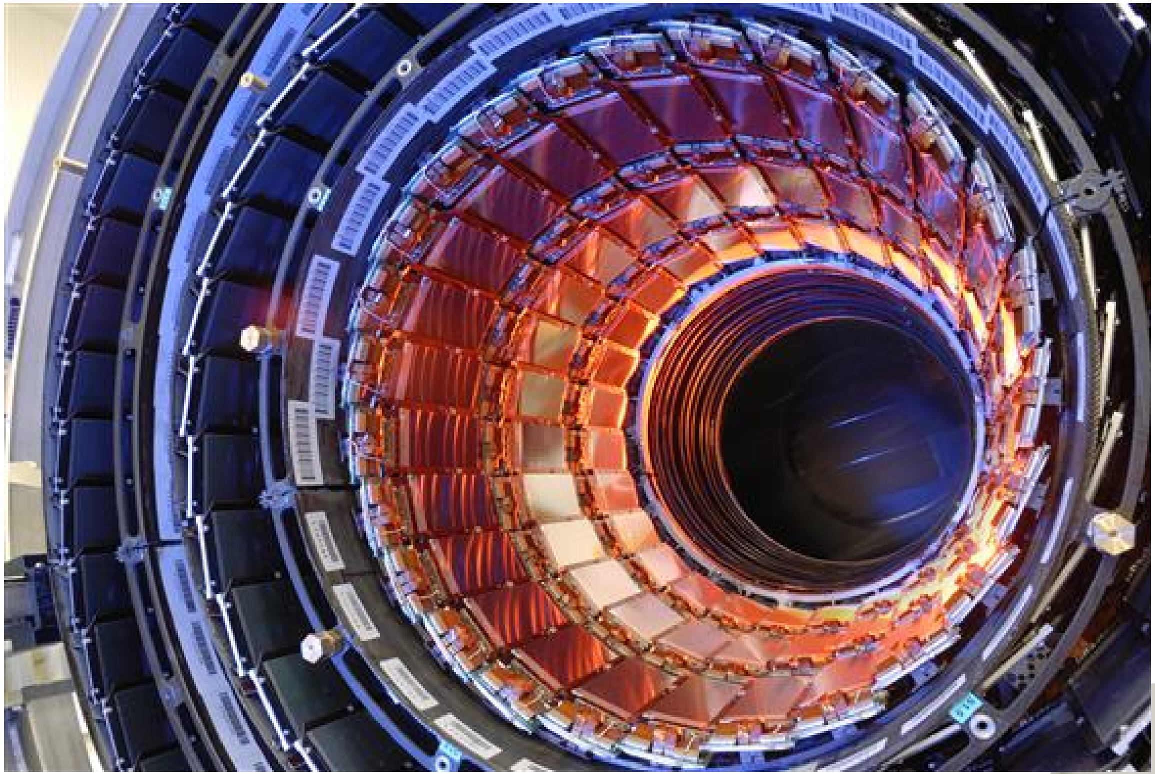


  - Analogue signal amplified, shaped and buffered in a pipeline (192x25ns)
- Sent via analogue optical link to FED for processing:
  - ADC + Data reduction (pedestal and noise subtraction, cluster finding)



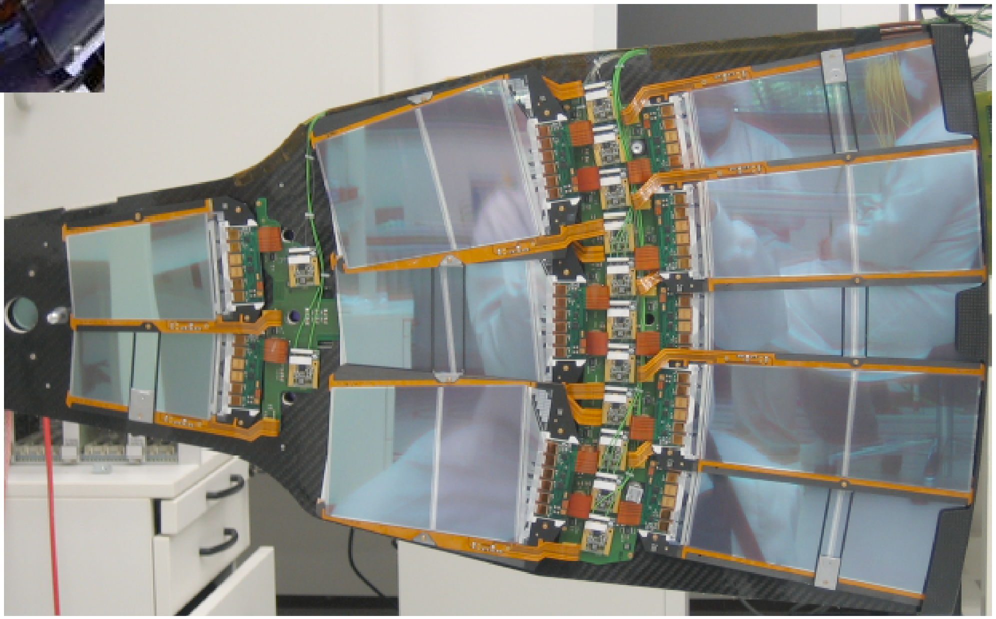

TEC modules
10cm

The Silicon Strip Tracker



3 layers of the TIB, with edges of the TID disks

TEC petal



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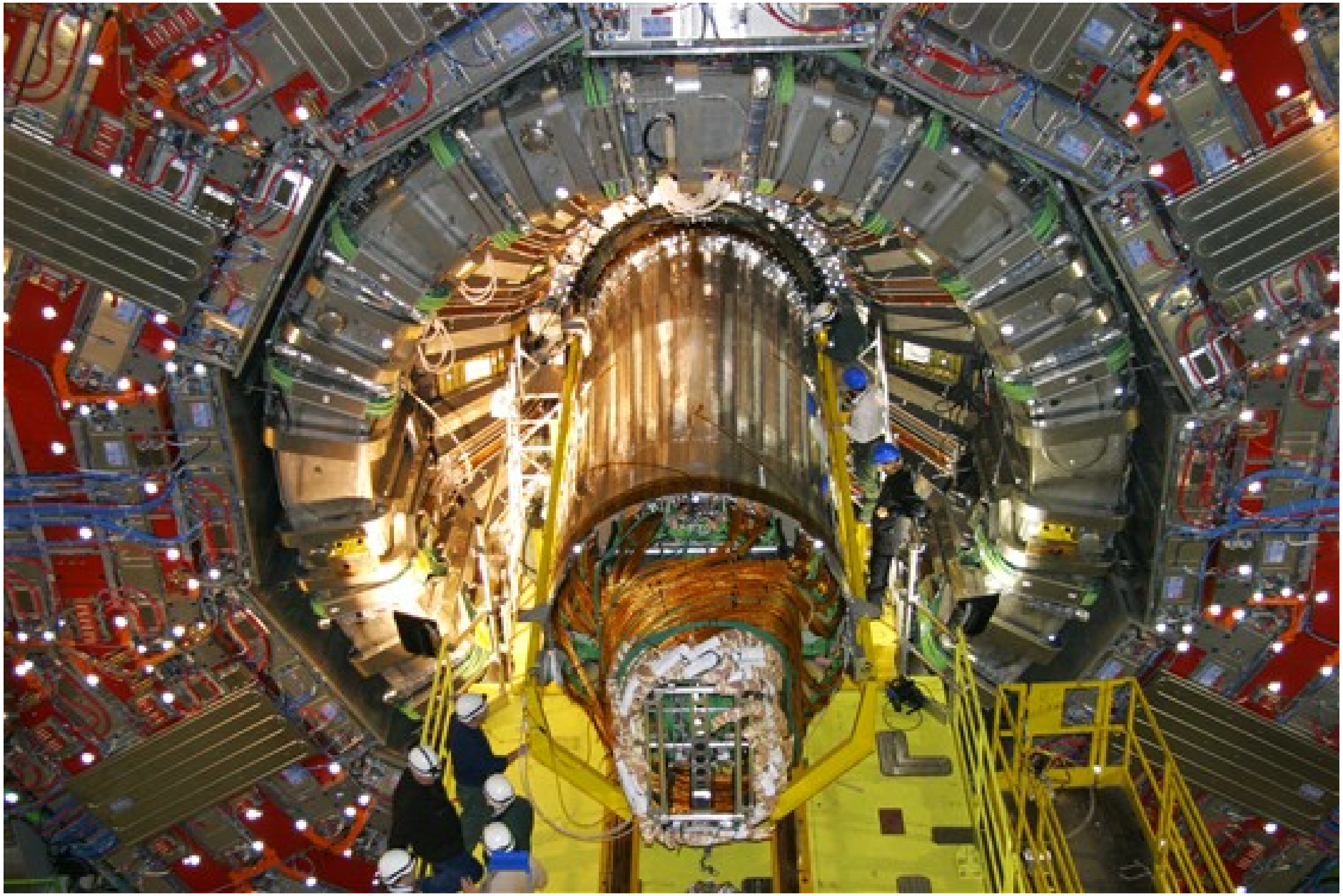
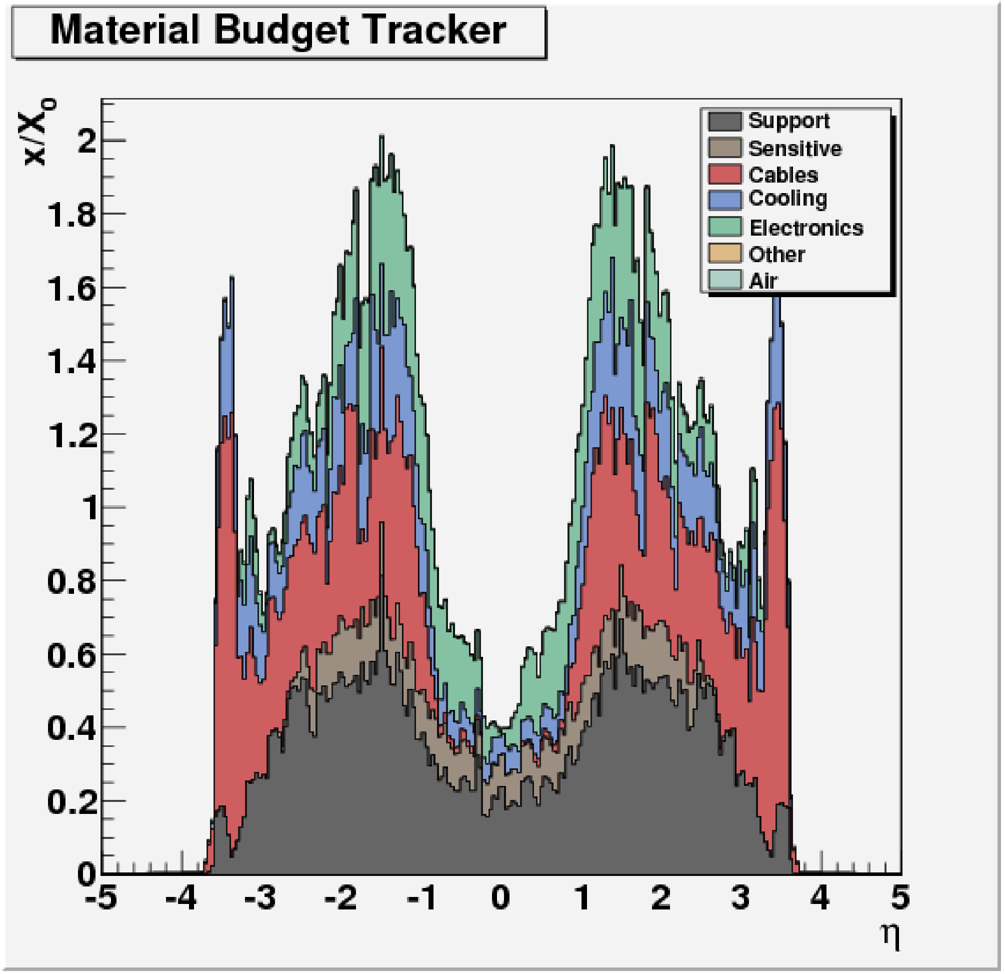
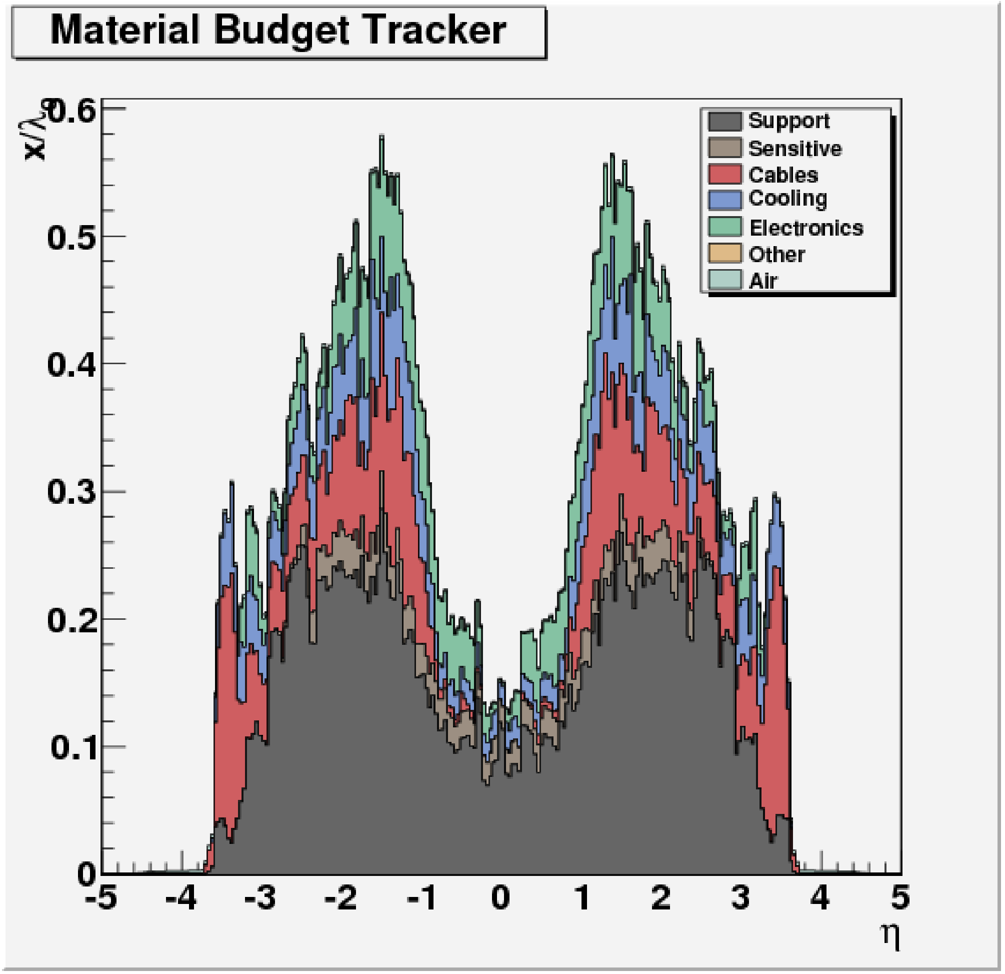


SST inserted in CMS
16 December 2007

Tracker Material budget



Material budget of the CMS tracker in units of radiation length



Material budget of the CMS tracker in units of interaction length

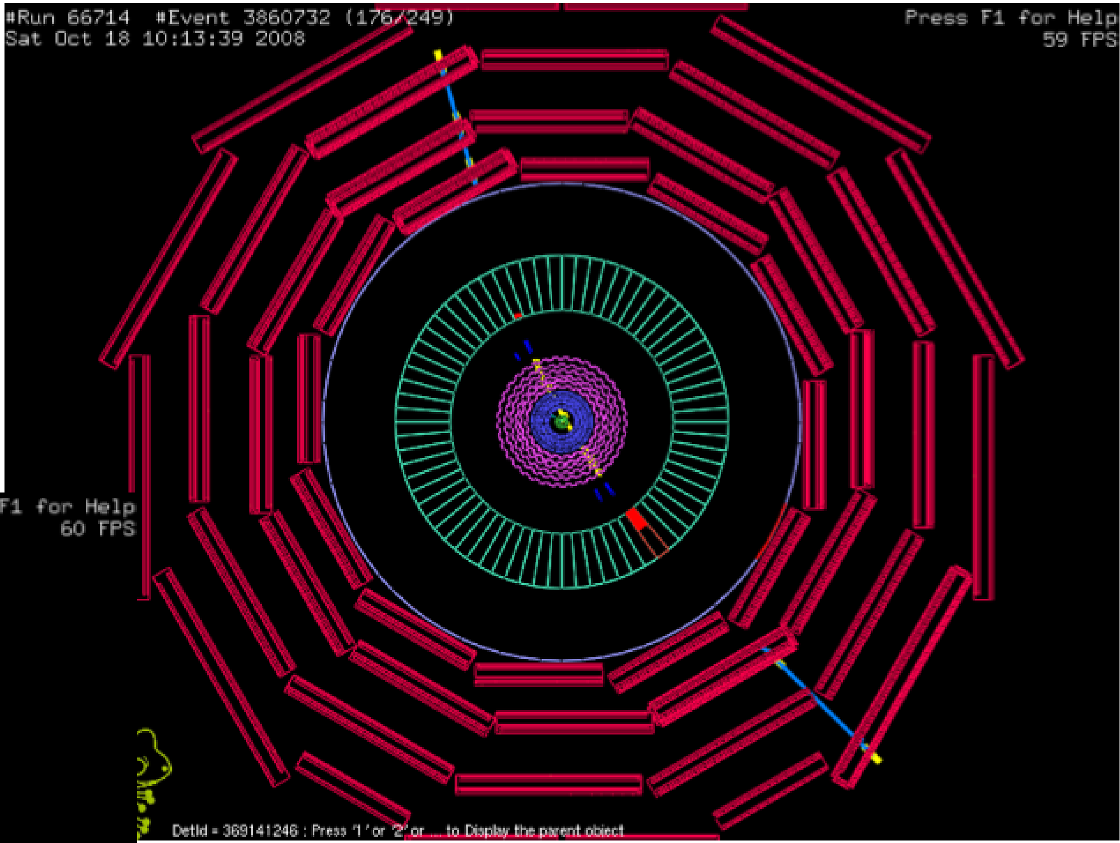
Timeline

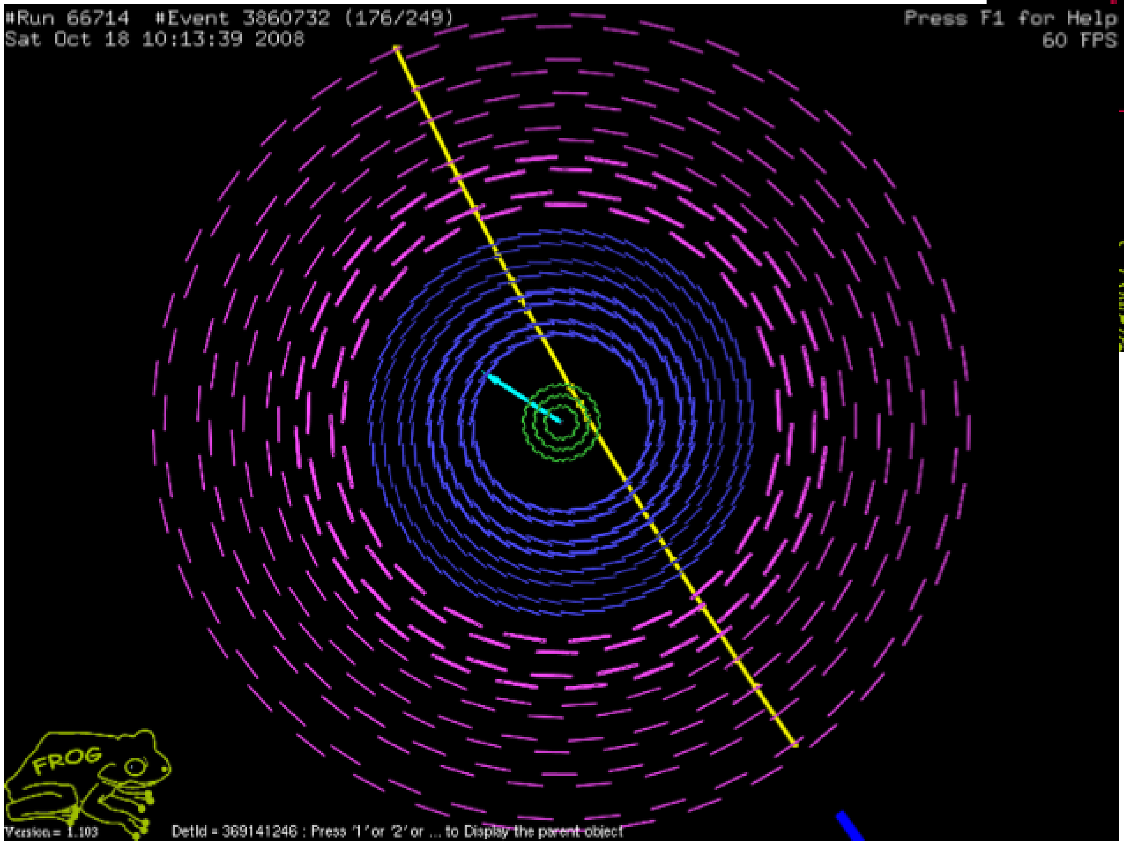
- Summer 2006: Slice test
  - Magnet Test and Cosmic Challenge, JINST 3 (2008) P07006
- November 2006 - July 2007: SST integration and commissioning at the Tracker Integration Facility (TIF)
- Sept 2007: Forward Pixel arrives at CERN
- Dec 2007: SST Installed in CMS
- Mar 2008: SST Fully cabled
- Jul 2008: Pixel inserted in SST
- Jul 2008: First “global run”
- Cosmic ray data-taking exercises:
  - CRAFT08: 27 days operation (15/10/08 to 11/11/08)
  - CRAFT09: 39 days operation (24/07/09 to 31/08/09)
- Dec 2009: First pp collisions at 900 GeV and 2.36 TeV
  - CMS recorded ~10 μb^{-1} data at 900 GeV and ~0.4 μb^{-1} at 2.36 TeV
- Mar 2010 : First collisions at 7 TeV

Cosmic ray data-taking exercises (CRAFT)

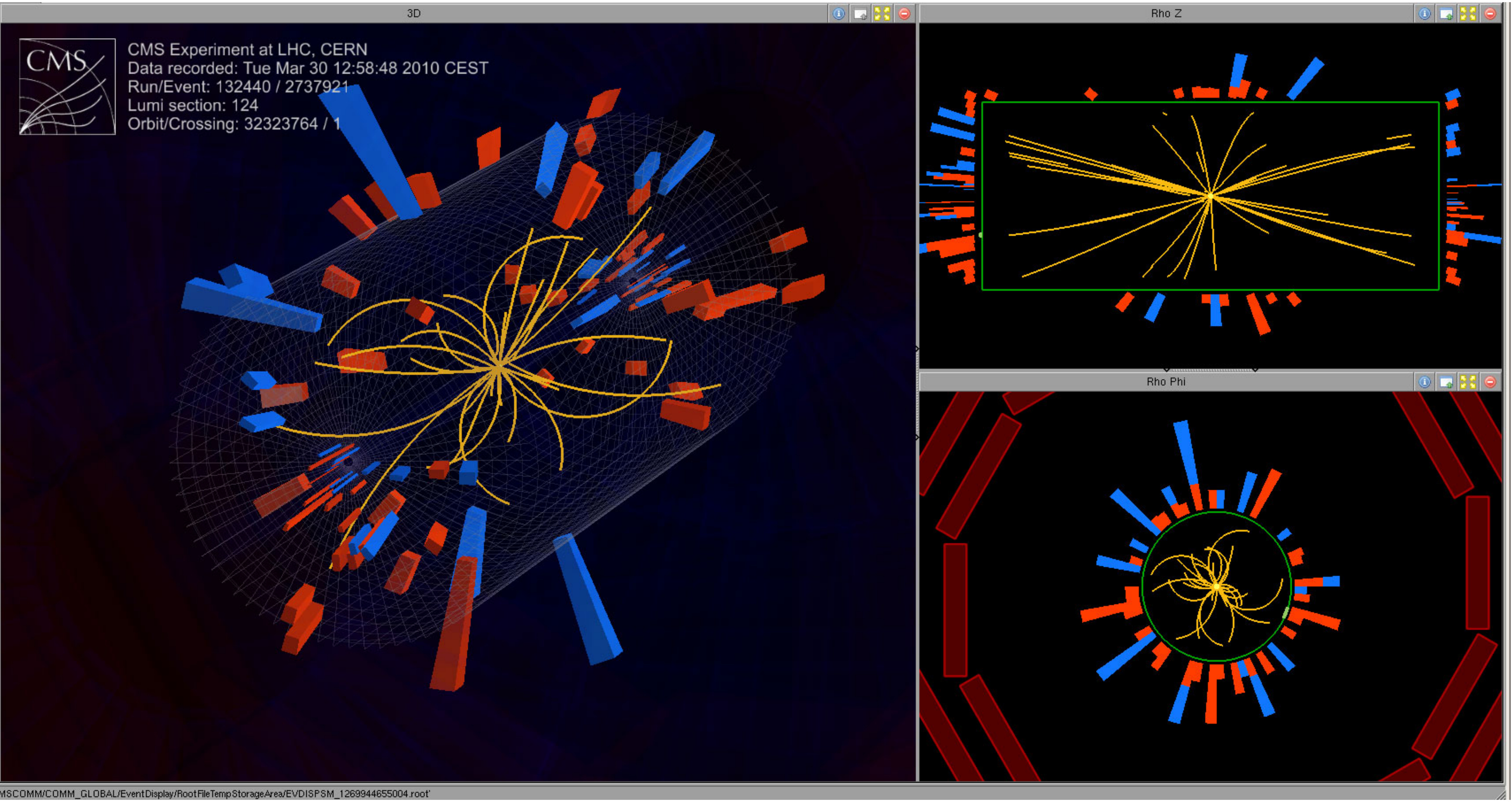
- CRAFT08: First experience with full tracker, in 3.8T magnetic field
  - Commissioning, calibration & alignment of the experiment for proton--proton collisions
  - Test procedures and workflows
  - ~ 270 M cosmic events selected → ~ 6.5 M events with tracks in Tracker
  - Allowed to establish the Tracker performance with
    - Remarkable agreement with specifications and simulations
    - High precision of calibration (few %)
    - Better alignment quality than originally foreseen
  - Analyse published in 3 papers (JINST)
- CRAFT09:
  - Validation of new commissioning with cosmic data
  - Calibration and alignment for first collisions
  - ~ 480 M cosmic events selected → ~ 10 M events with tracks in Tracker

Cosmic ray event display





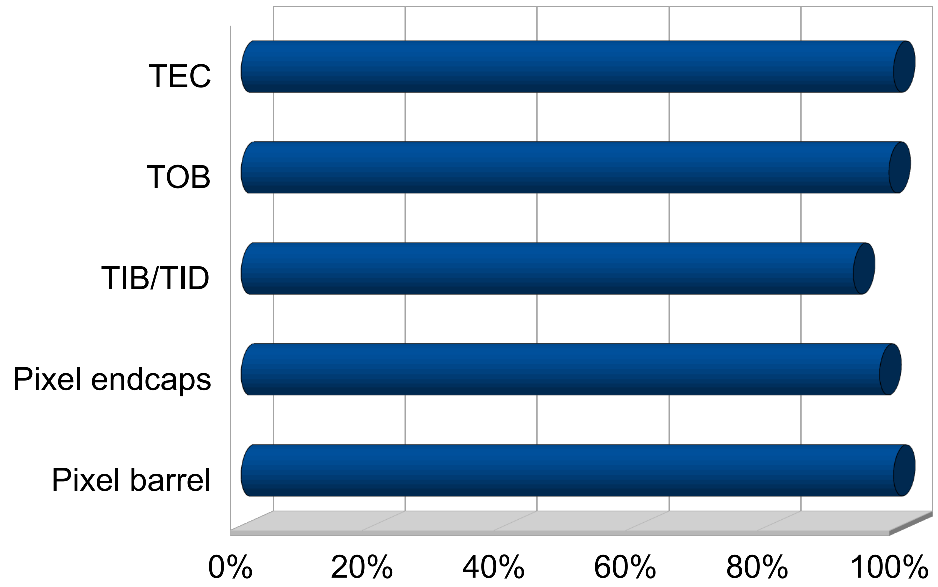
Event display of 7 TeV collision



Operational Fraction of Strip and Pixel Tracker

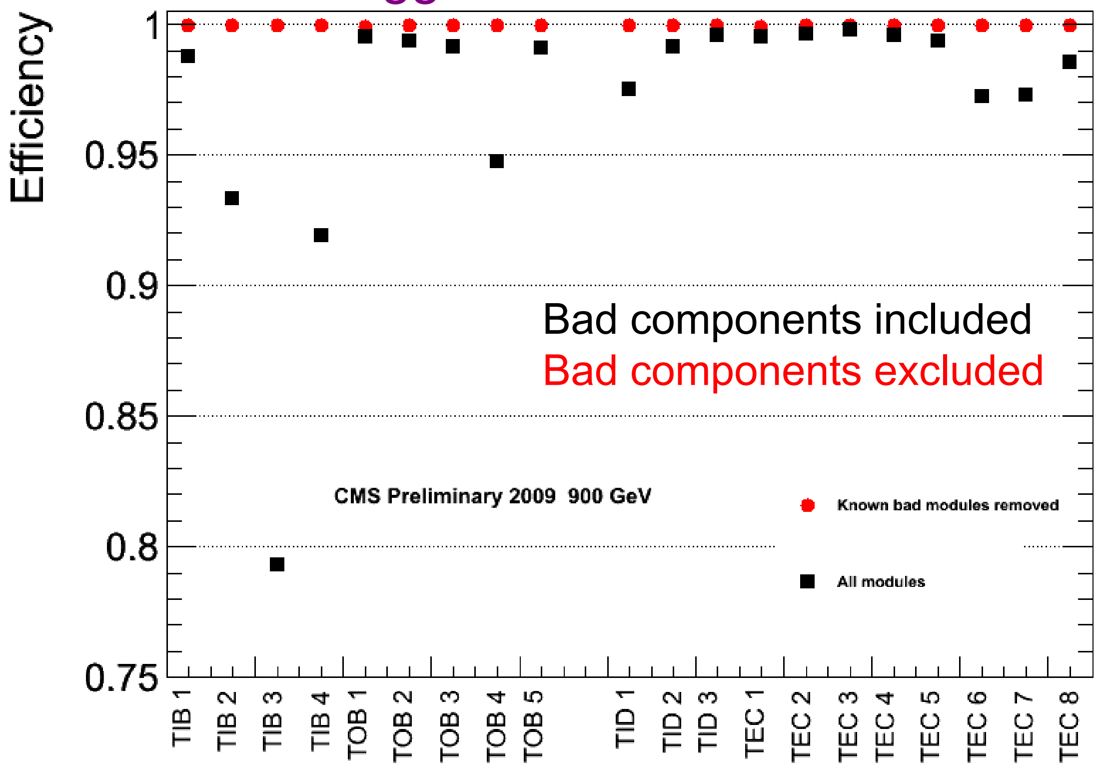
Operational Fraction in December 2009 pp collisions:

- Pixel: 98.4% of channels in operation
  - Barrel: 99% (11400 out of 11520 ROCs operational)
  - Endcap: 96.9% (4185 out of 4320 ROCs)
- SST: 97.2% of channels in operation
  - TIB/TID: 92.9 %
    - ~2% recovered since then
  - TOB: 98.3 %
  - TEC: 99.0 %



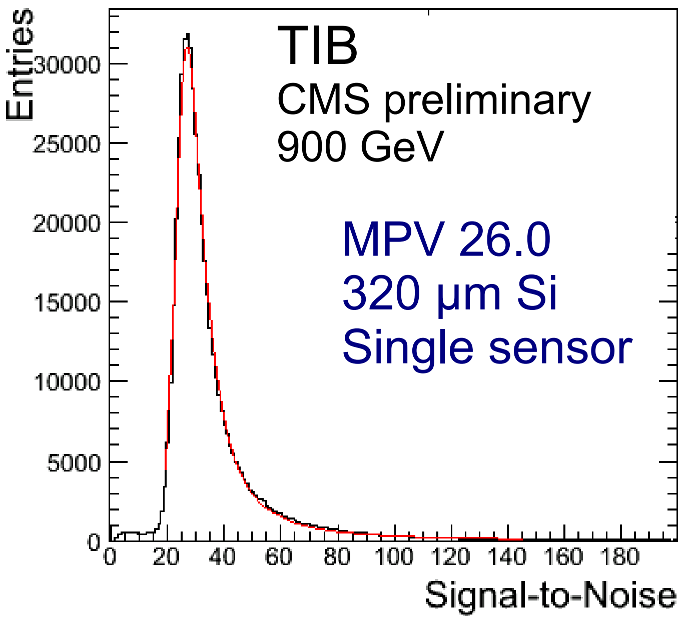
Sensor efficiency

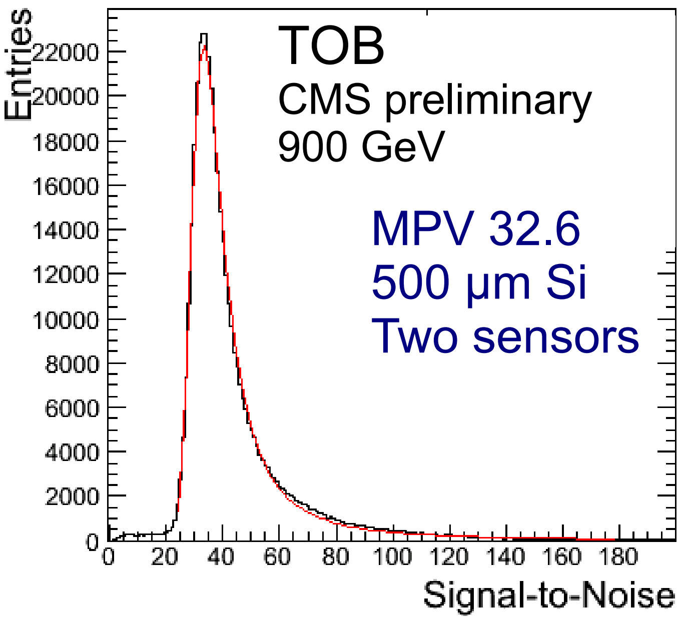
- Sensor efficiency measured with reconstructed tracks:
  - Search compatible hit from track extrapolation (removing sensor edges and layer under study)
- Powerful validation of bad components identification
- Missing components taken into account in track reconstructions
- Pixel efficiency ~ 97%, measured in CRAFT08
  - Deficit due to random arrival time of cosmic trigger
- Strips: >99.9 % after removal of faulty components



Strip tracker S/N

- Path length corrected signal-to-noise ratio, peak mode

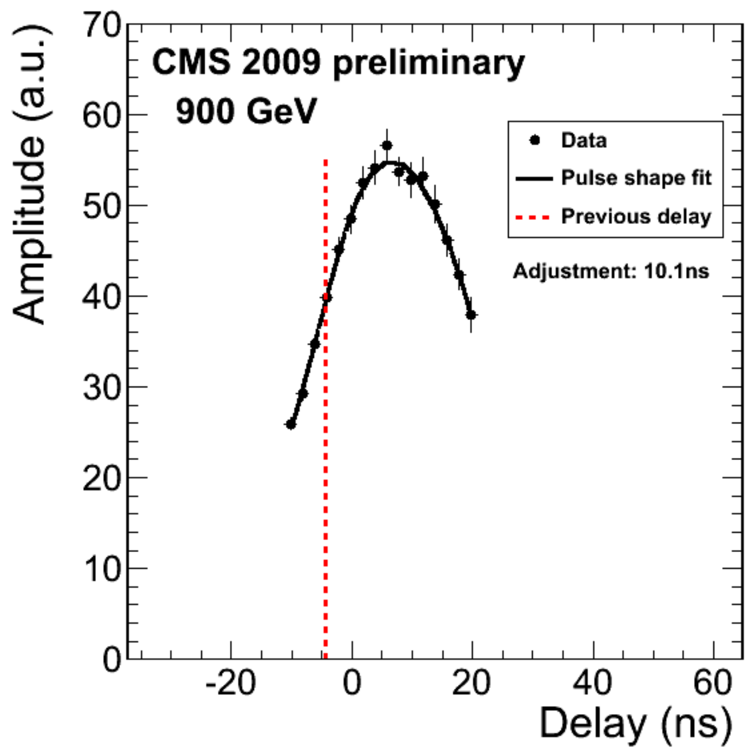




  - More signal with increasing silicon sensor thickness (typical MIP: 25000 e^-/320µm)
  - More noise with increasing capacitance (strip length)

Strip tracker S/N

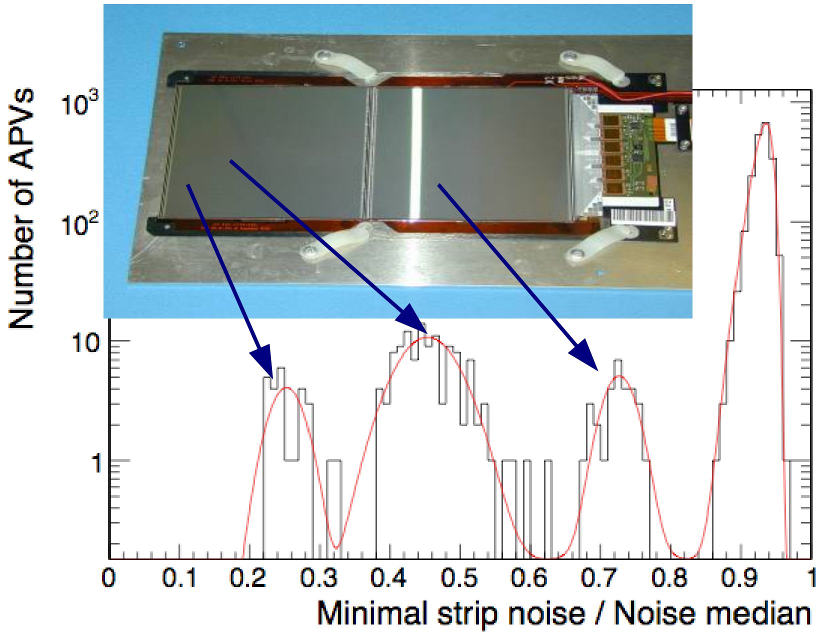
- In CRAFT and Dec2009 collisions, Strip tracker operated both in Peak and Deconvolution modes
  - Deconvolution: nominal mode of operation
- For Deconvolution:Time delay scan to determine maximum charge collection
- Peak vs. Deconvolution S/N scales as expected, ratio ~1.7
  - Detector properly timed
  - Noise increase: ~50%
  - Signal reduction ~10%

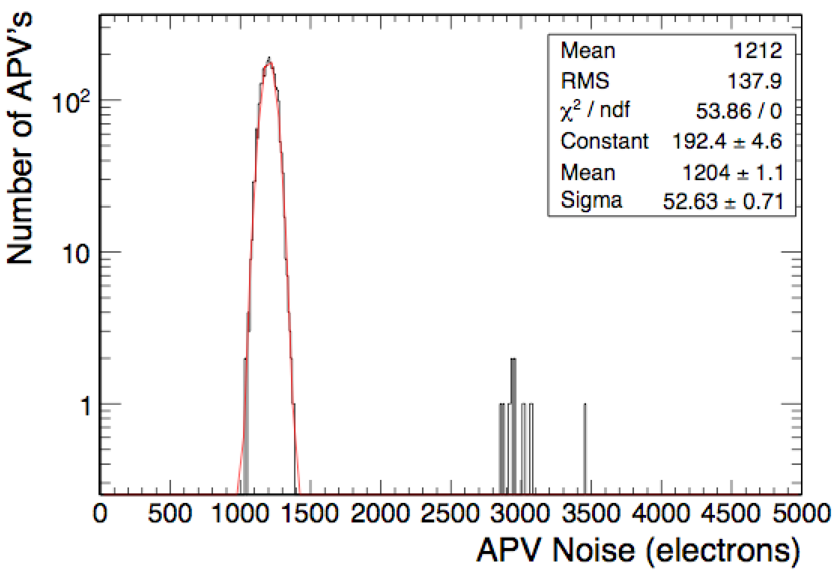


Mode	TIB	TID	TOB	TEC thin	TEC thick
Peak	26.0	26.0	32.7	27.9	36.0
Deconv	19.5	19.4	24.5	18.8	24.1

Noise

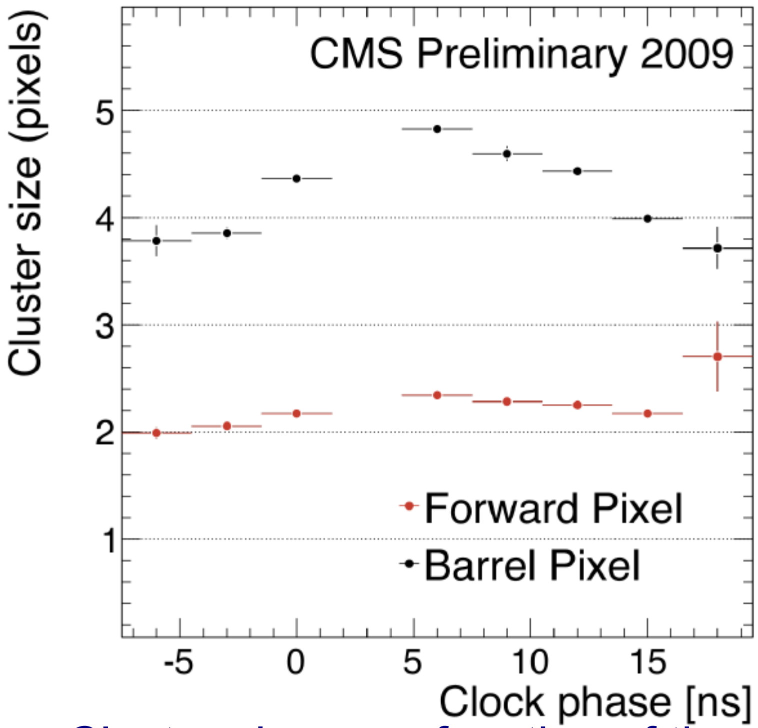
- Pixels
  - Overall noise < 2% of Signal (dominated by read-out chain after the ROC)
  - Noisy Pixels < 0.5 x 10^{-5}
- Strips
  - Noise(e^-) = (427 ± 39) + (38.7 ± 3) × Strip length(cm)
  - Sensitive to missing HV, dead and noisy channels and non Gaussian channel noise behaviour
  - Identify noise sources due to changes in capacitance:
    - Missing APV-PA bonds, PA-sensor bonds, sensor-sensor bonds



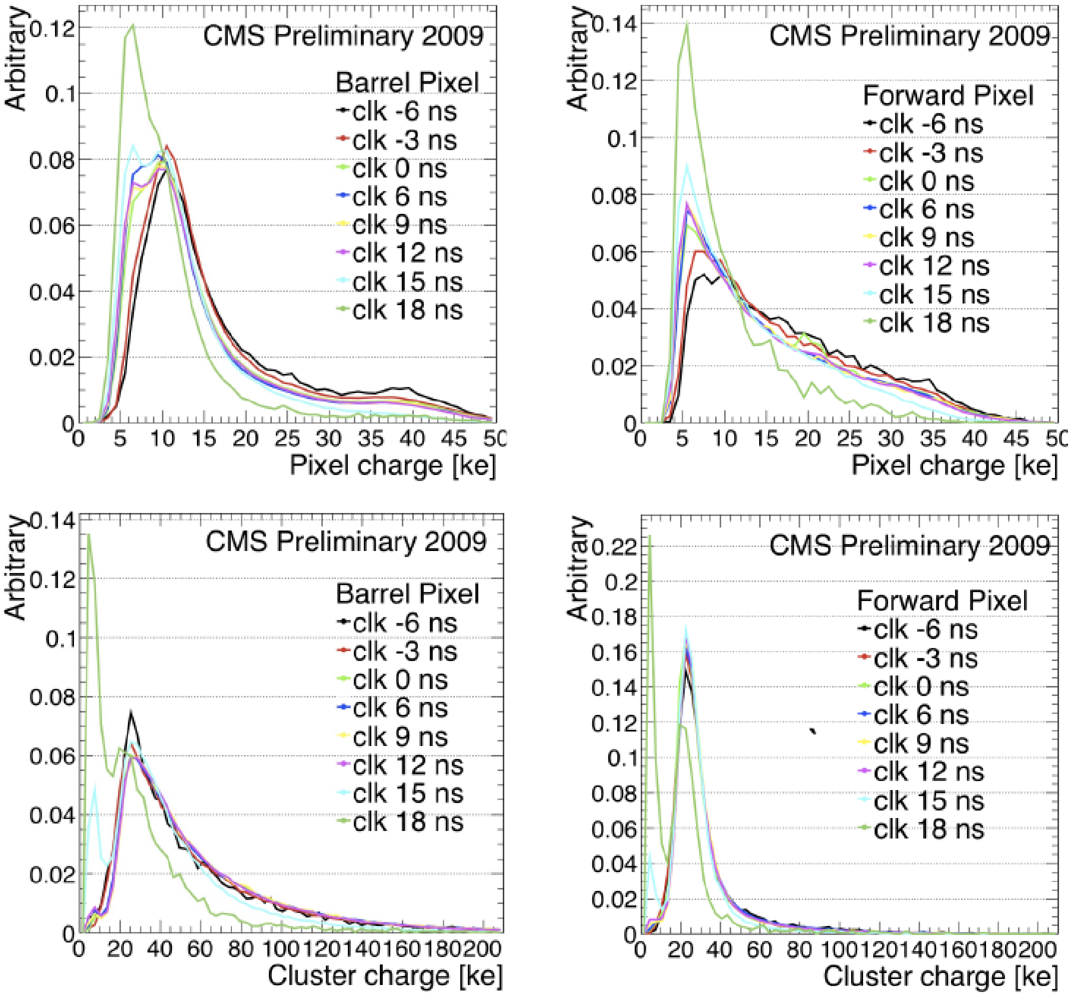


Pixel timing scan

- Coarser timing scan, suitable for first runs
  - Pixel with Large pulse height go over threshold first
  - Small pulse heights later
- Optimal point at +6ns
- Fine-grained scan and detailed analysis being done



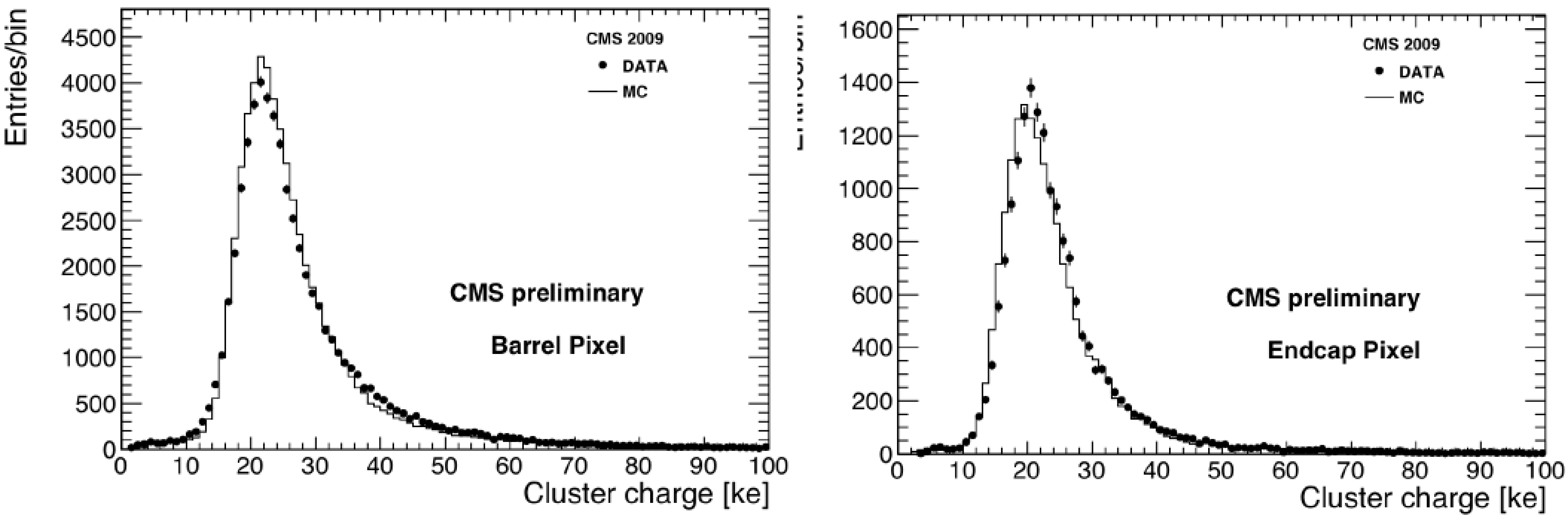
Cluster size as a function of the clock phase



Individual pixel and total cluster charge for different delays.

Pixel Cluster Charge

- Total cluster charge corrected for track impact angle w.r.t. the sensor
- Cluster charge in data ~ 20 ke$^-$ compatible within 5% with CMSSW MIP simulation
  - Gains Measured at pixel level with 20% rms (15% rms in charge injection)
  - Particle signal from beam collisions will improve inter-calibration resolution



Hit resolution

- Use hits in overlapping modules in the barrel:
  - Fit width of residual of double difference of hit and track position
  - Minimize multiple scattering and extrapolation effects
  - Not sensitive to alignment (at first order)
- Pixels:

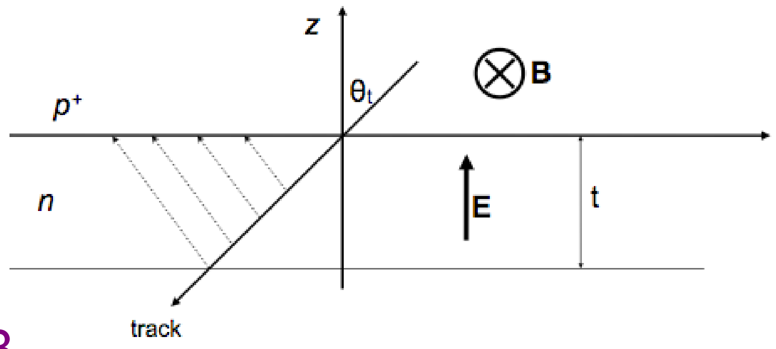
Coordinate	r-φ	z
Data (μm)	18.6±1.9	30.8 ±3.2
Simulation (μm)	22.1±0.2	28.5 ±0.1

- Strips:

Sensor [μm]	Pitch [μm]	Resolution [μm]	Track angle			
			$0° - 10°$	$10° - 20°$	$20° - 30°$	$30° - 40°$
TIB 1-2	80	Measurement	17.2 ± 1.9	14.3 ± 2.3	17.4 ± 3.2	25.7 ± 6.0
		MC Prediction	16.6 ± 0.5	11.8 ± 0.5	12.4 ± 0.6	17.9 ± 1.5
TIB 3-4	120	Measurement	27.7 ± 3.6	18.5 ± 3.1	16.1 ± 3.1	24.1 ± 6.7
		MC Prediction	26.8 ± 0.7	19.4 ± 0.8	17.2 ± 0.3	21.4 ± 2.0
TOB 1-4	183	Measurement	39.6 ± 5.7	28.0 ± 5.8	24.8 ± 6.5	32.8 ± 8.3
		MC Prediction	39.4 ± 1.3	27.8 ± 1.2	26.5 ± 0.3	32.5 ± 2.1
TOB 5-6	122	Measurement	23.2 ± 3.6	19.5 ± 3.6	20.9 ± 6.1	29.3 ± 9.7
		MC Prediction	23.8 ± 0.9	18.0 ± 0.5	19.2 ± 1.2	25.4 ± 1.6

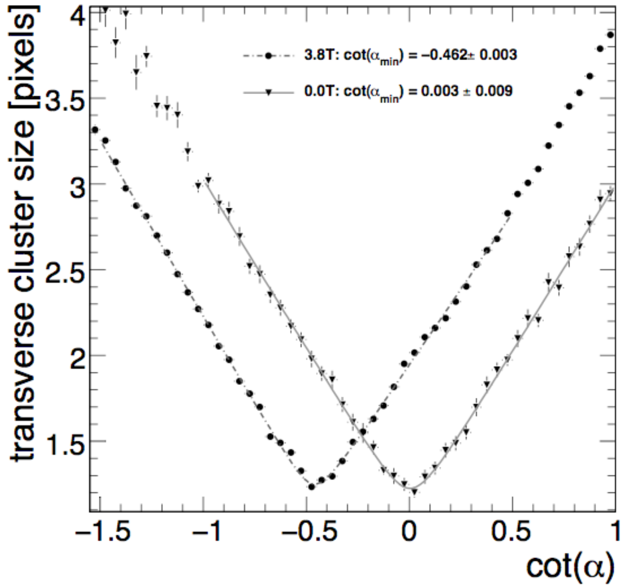
Lorentz Angle measurement

- E and B fields perpendicular in the Barrel



- Lorentz angle improves charge sharing and resolution
- Causes bias in cluster position:
  - ~130µm BPIX, ~20µm FPIX, ~10µm TIB/TOB
- Minimum of cluster width:

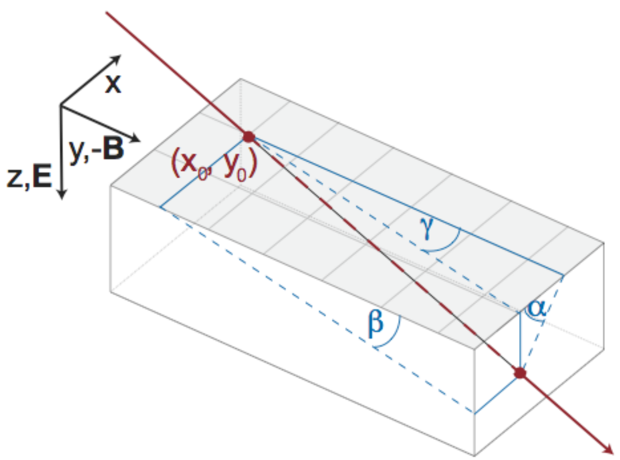
BPIX	FPIX	TIB	TOB
24.8°	4.2°	3.9°	5°

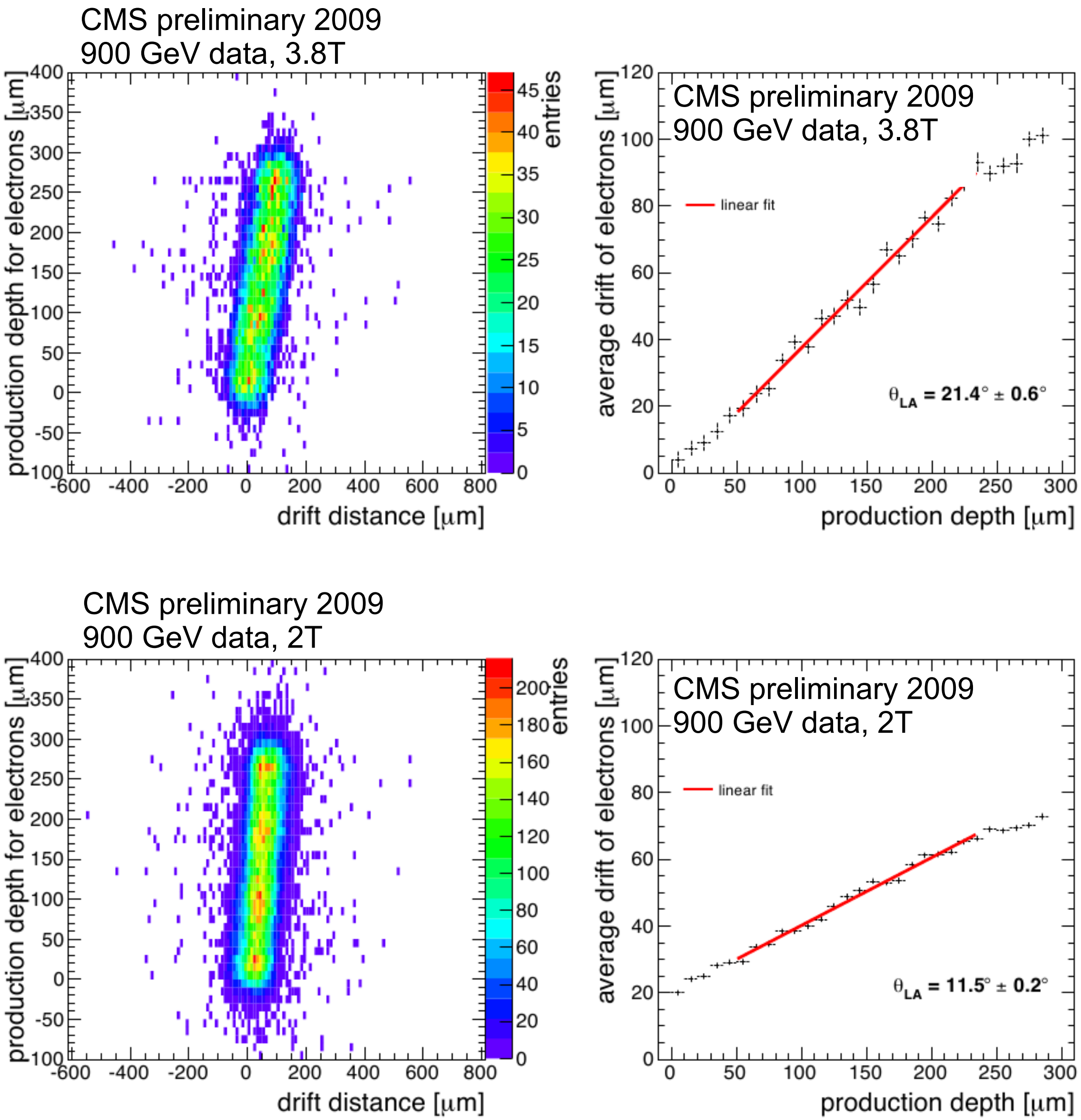


  - Pixels compatible with model within 3% uncertainties
  - Strips: 25(14)% lower than model (not yet understood)
    - New method developed, to be use with collisions

Lorentz Angle measurement

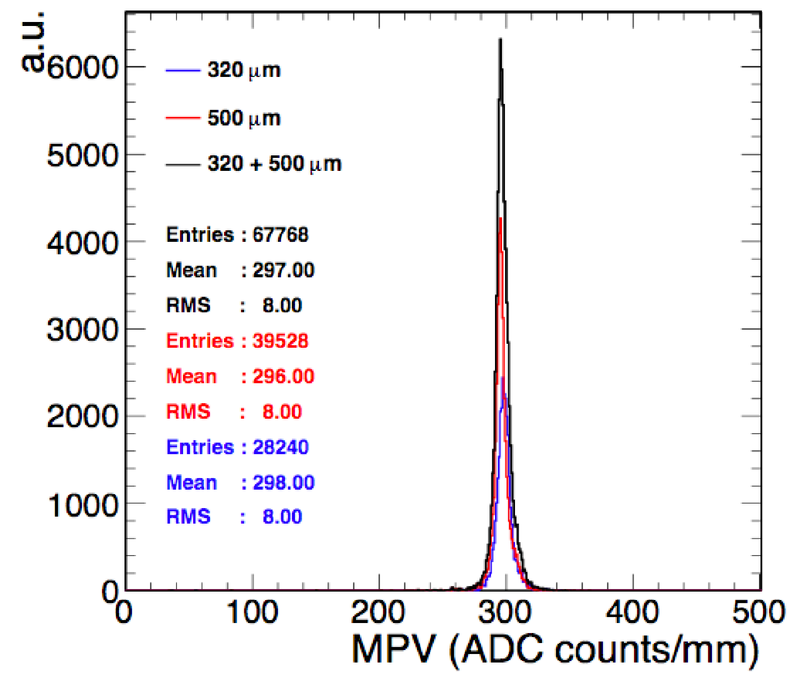
- In collisions, Lorentz angle measured in the pixels using the grazing angle method.
- Results for 3.8T and 2T agree well with MC.

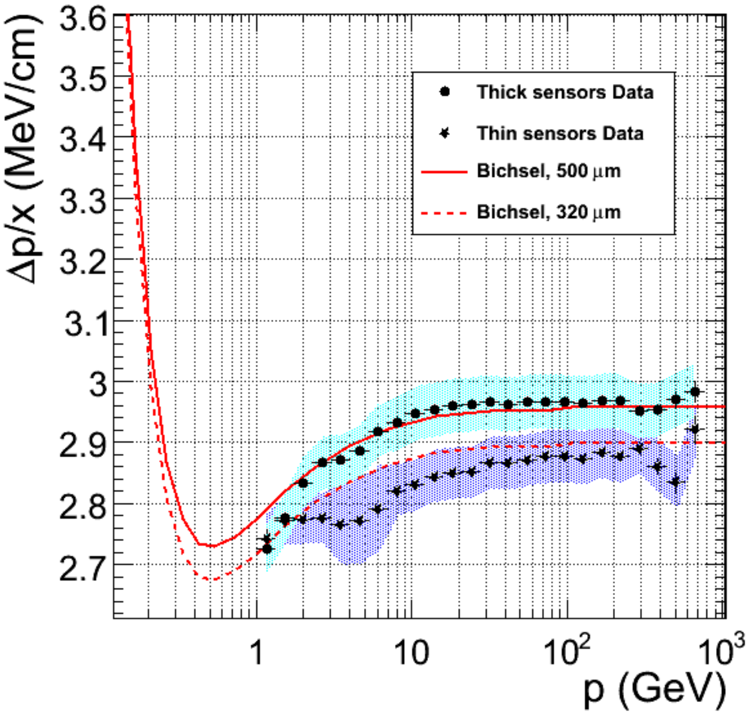




Energy calibration

- For dE/dx, precise energy calibration needed
- Using Cosmic muons (MIP)
- Adjust Path length corrected MPV to MIP signal (at APV level)
  - 262 ± 3 e⁻/ADC compared with 269 e⁻/ADC from pulse injection

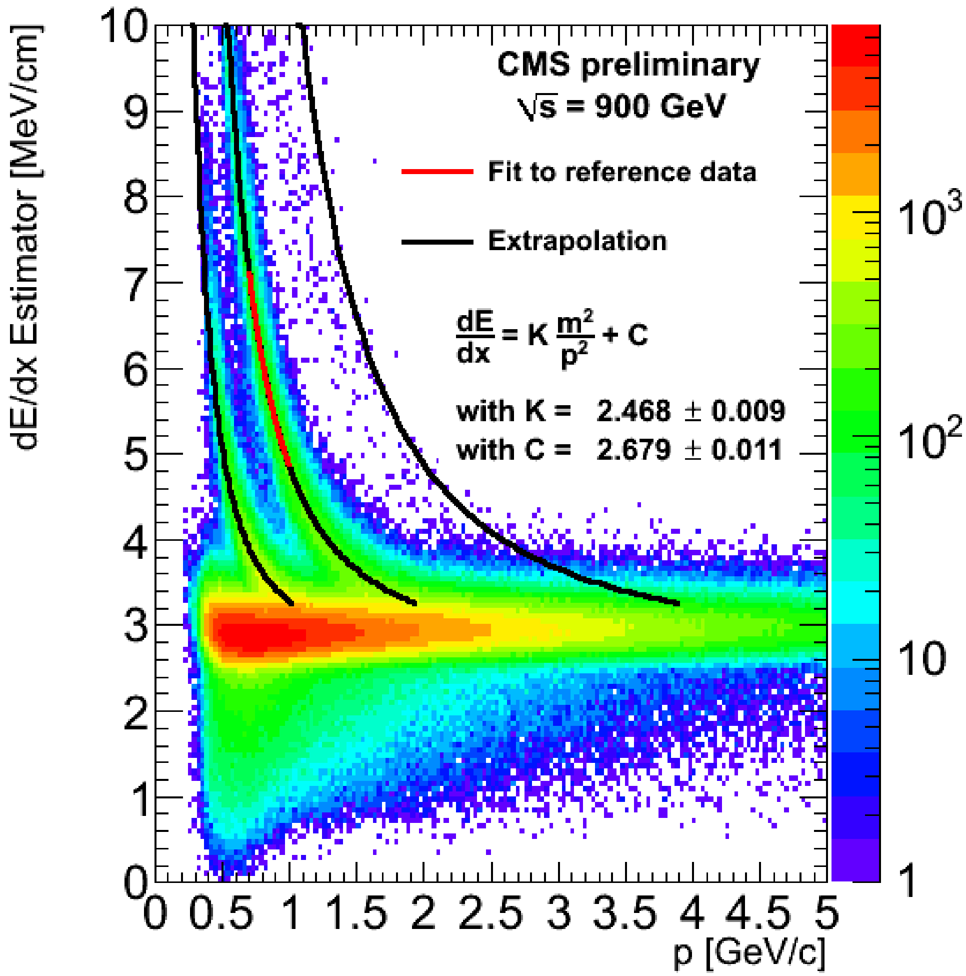




Absolute calibration from Δp/x adjusted to Bichsel function

- Most probable energy loss/unit length
- Fit as function of track momentum
- Extract calibration constant for each sensor type

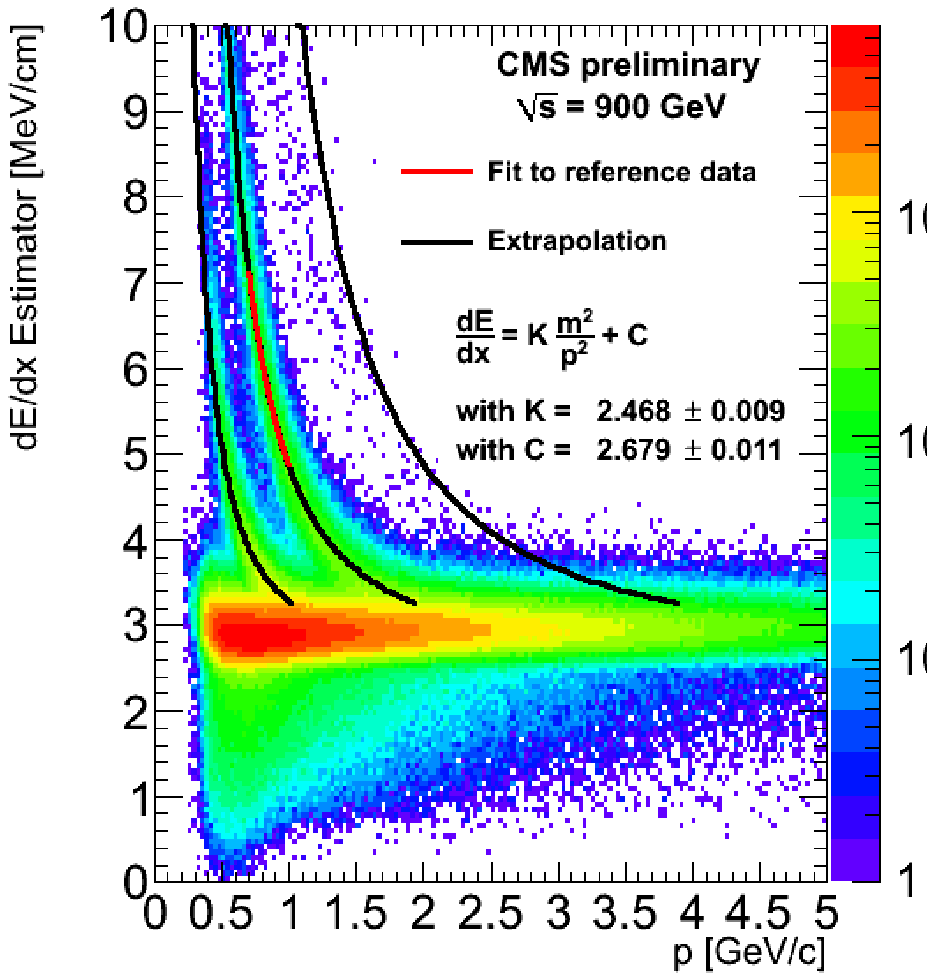
dE/dx measured during collisions:



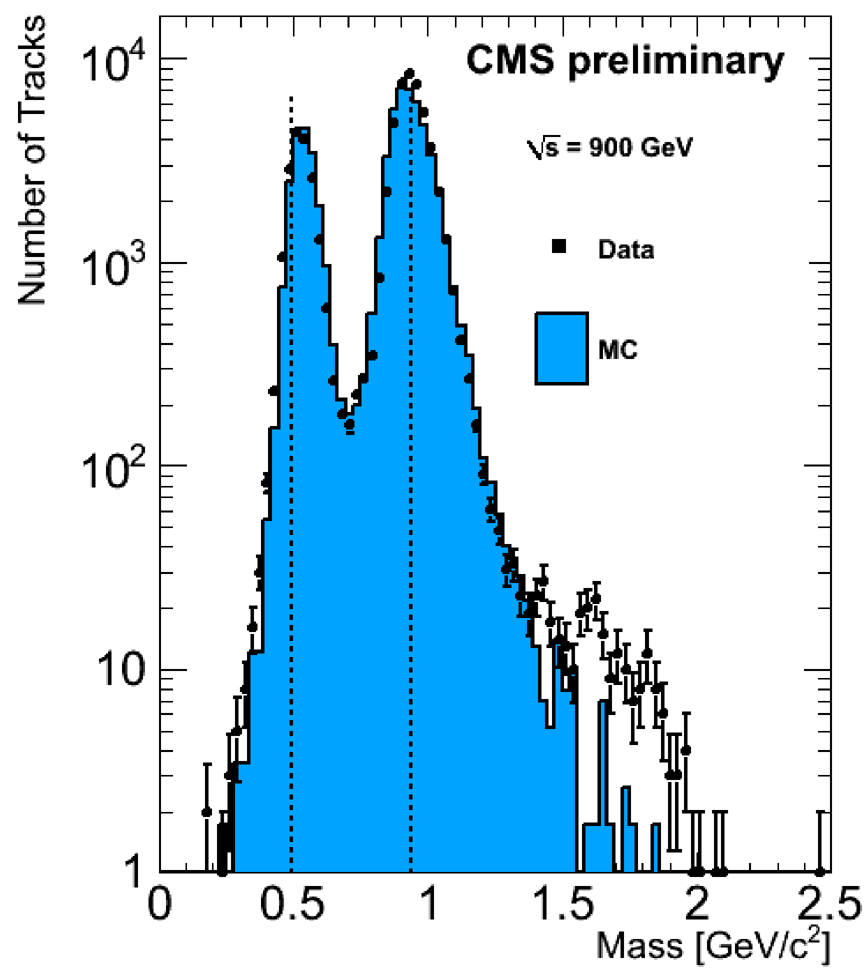
Fit of dE/dx vs. P from proton line (red), and extrapolated

dE/dx

dE/dx measured during collisions:



Fit of dE/dx vs. P from proton line (red), and extrapolated

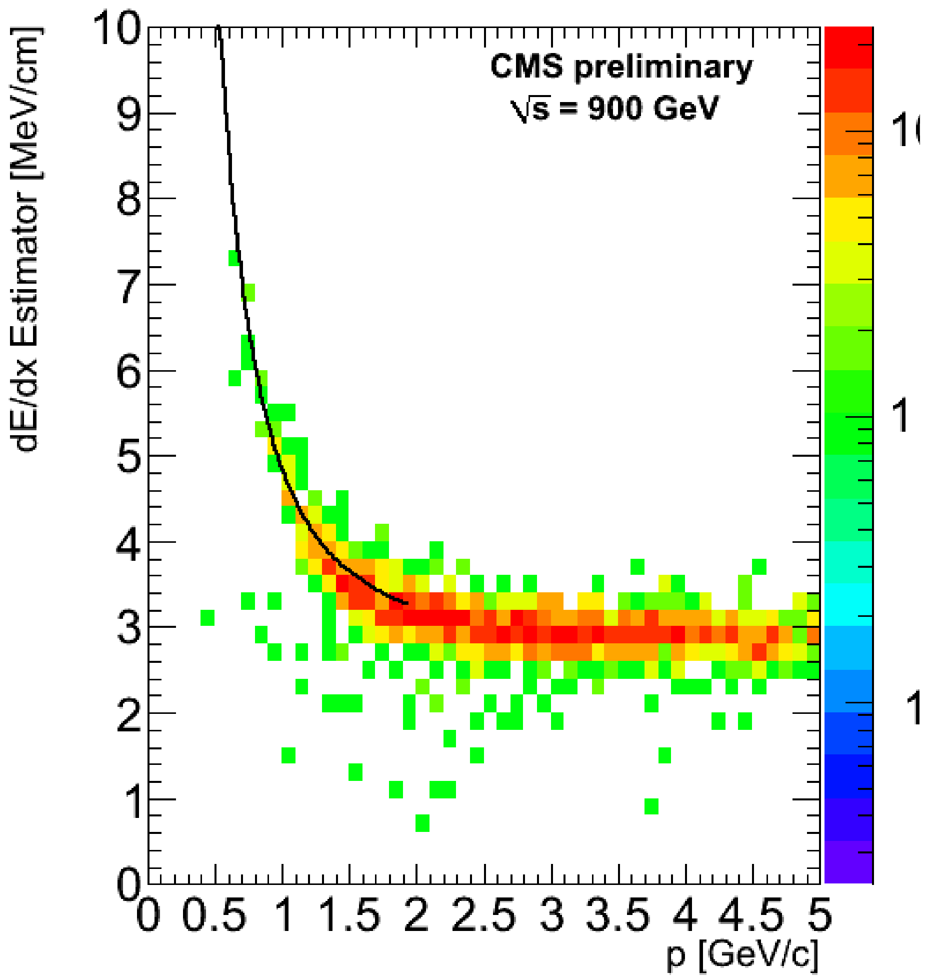


Mass distribution of Particles with dE/dx>4.15 MeV/cm, p < 2 GeV/*c*

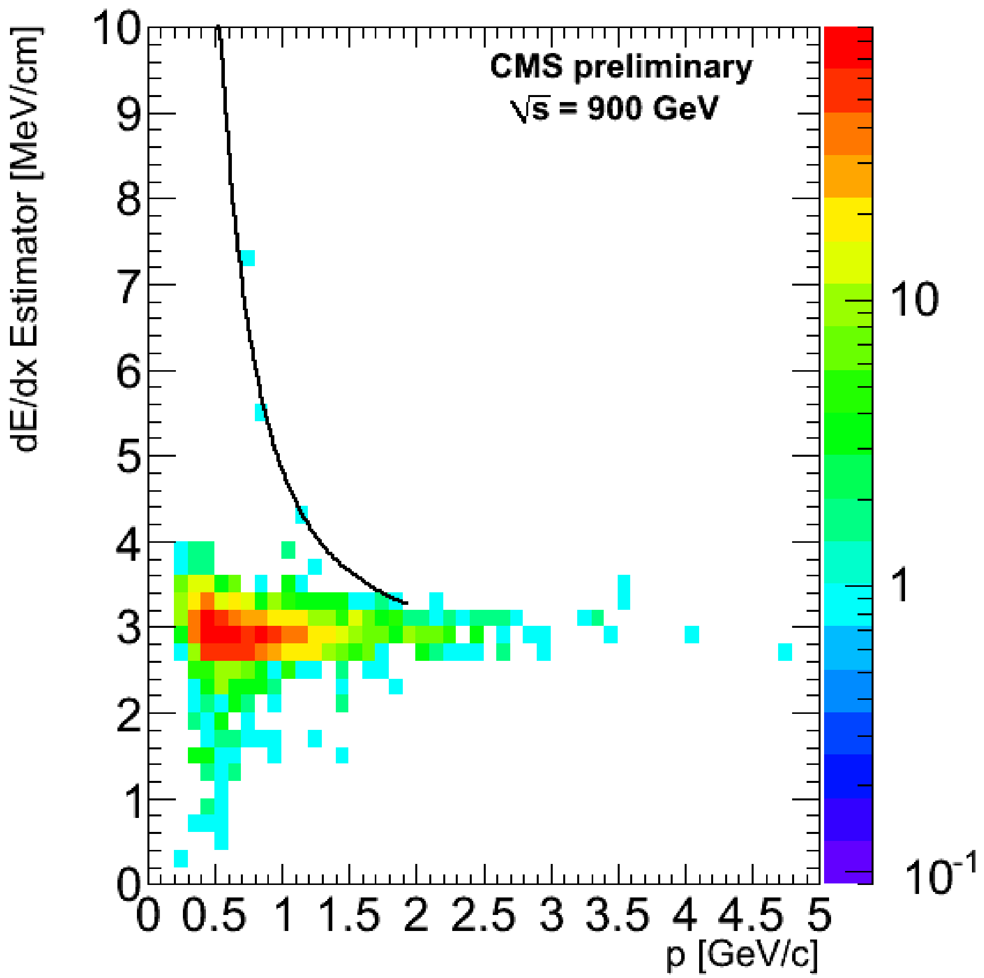
Proton and Kaons clearly visible !

Validation of dE/dx using $\Lambda \rightarrow p\pi^-$ decays:

- Reconstructed Λ: proton with higher momentum than pion



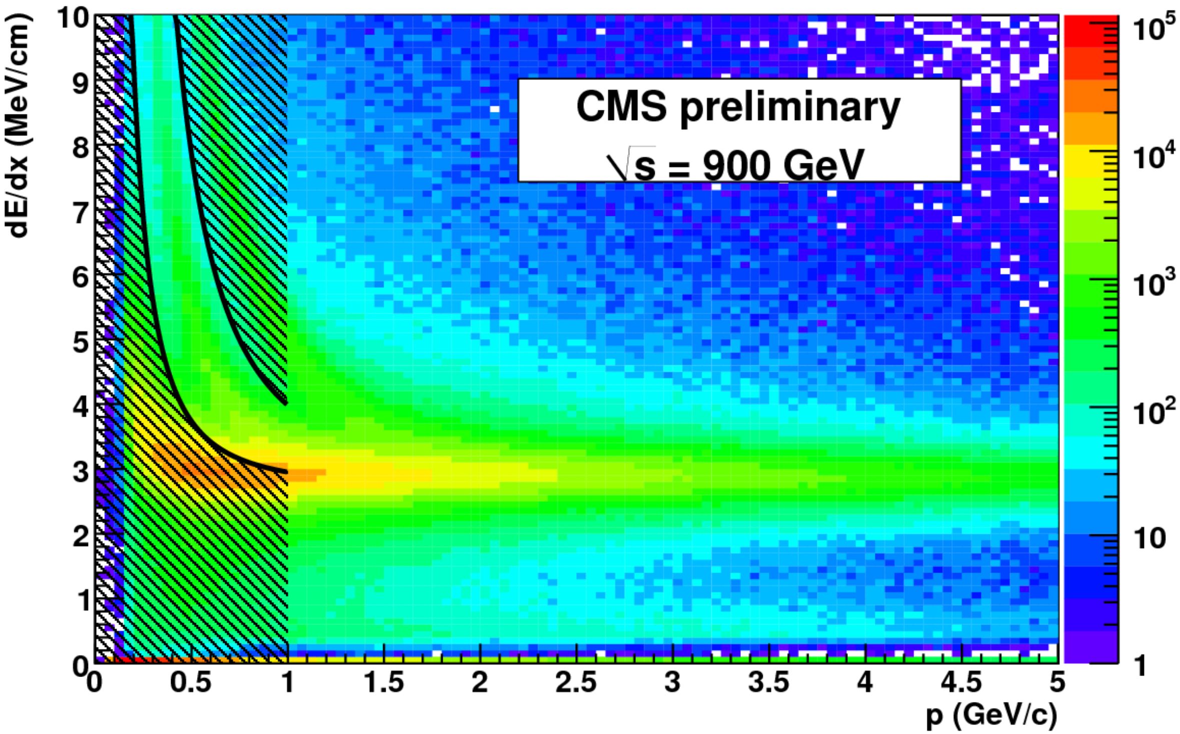
dE/dx of track with higher p_T



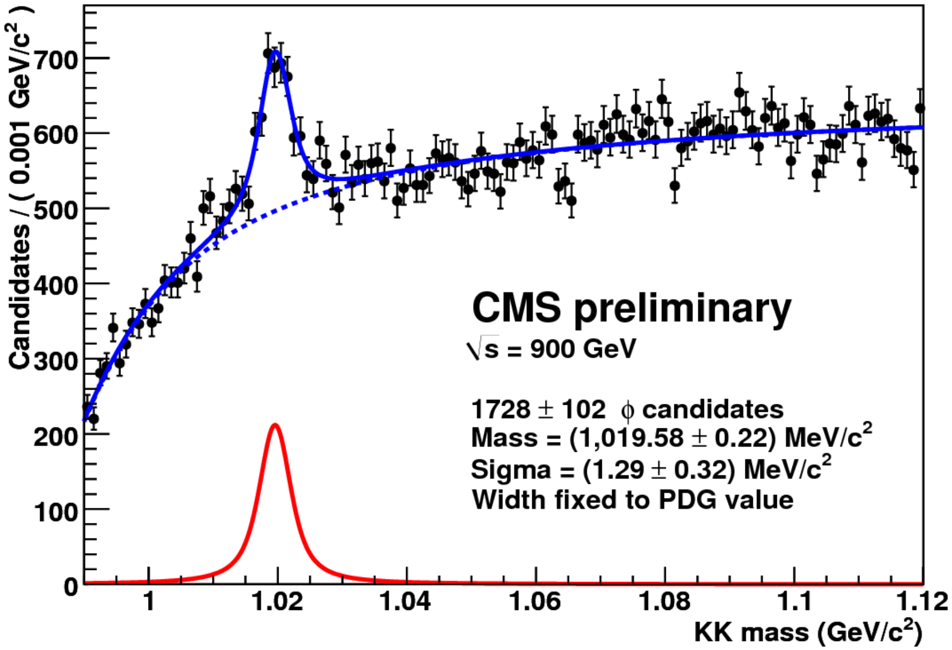
dE/dx of track with lower p_T

Reconstruction of φ meson

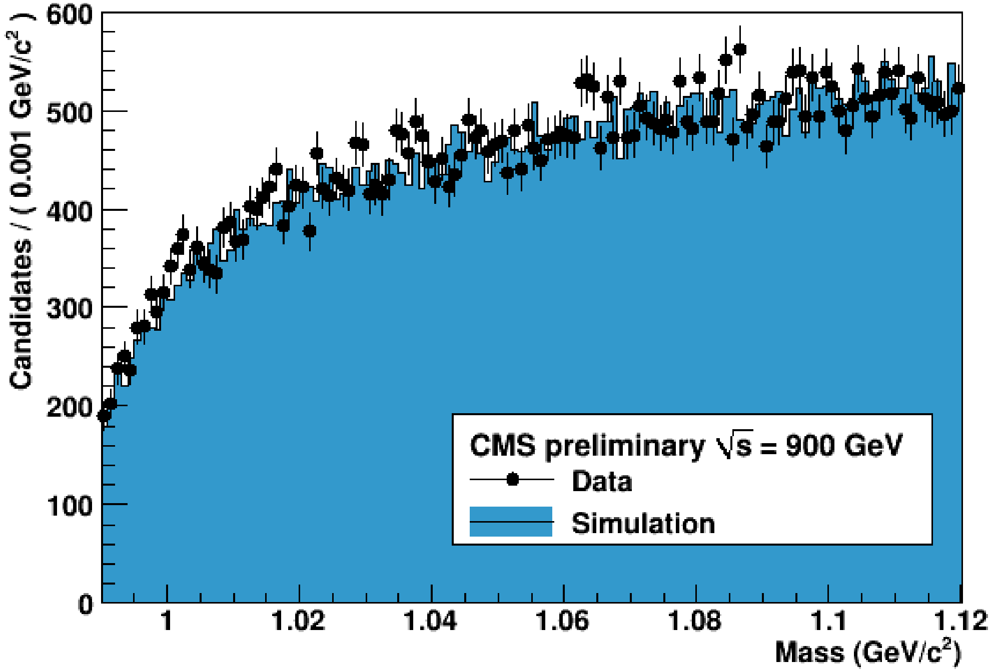
- Reconstruction of φ(1020) → $K^+ K^-$, using dE/dx for PID:
  - High quality tracks
  - Compatible with the Primary vertex
  - p > 1 GeV/*c* or dE/dx corresponding to M in the range of M_K ± 200 MeV/c^2



Reconstruction of φ meson



Mass distribution of kaon candidate pairs



Mass distribution of pairs when at least one track fails the dE/dx requirement

Conclusion

- CRAFT exercises:
  - Commissioning, calibration & alignment of the experiment for proton-proton collisions
  - Allowed to establish the Tracker performance with
    - Remarkable agreement with specifications and simulations
    - High precision of calibration (few %)
    - Better alignment quality than originally foreseen
  - Test procedures and workflows
  - CRAFT08 Analyse published in 3 papers (JINST)
- Dec 2009: First pp collisions at 900 GeV and 2.36 TeV
  - CMS recorded ~10 μb^{-1} data at 900 GeV center of mass energy, and ~0.4 μb^{-1} at 2.36 TeV
  - First results from the tracker and track reconstruction to be published soon
- Mar 2010 : First collisions at 7 TeV

Conclusion

- The Tracker is an exceptional scientific instrument
  - Largest silicon tracker ever build, with 200 m^2 of silicon sensors!
  - Very good performance
  - Well prepared for coming physics analysis
- Very capable tracker
  - Low occupancy
  - Reconstructed hits have a high purity and high S/N
- Robust and versatile tracker, with sufficient redundancy to operate in a very challenging environment

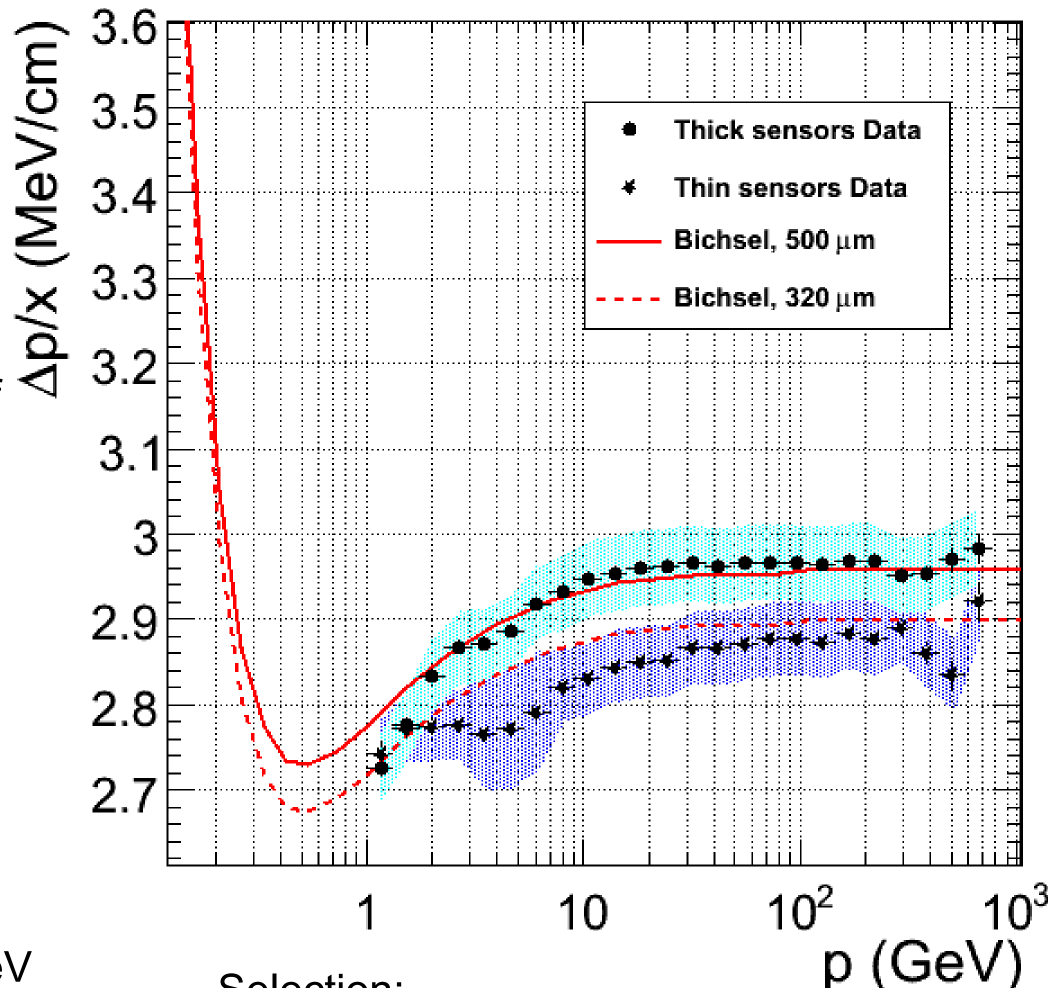
Backup

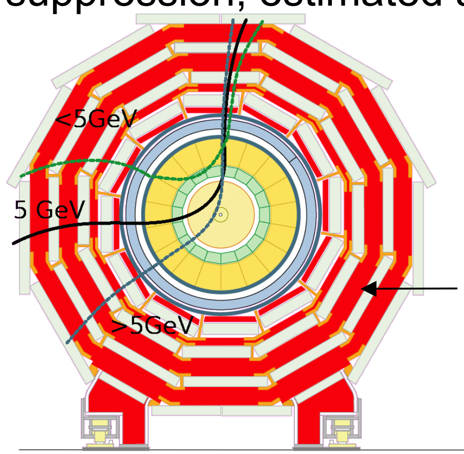
Energy loss in silicon strip tracker

The energy loss in silicon is measured in the range from 1GeV to 10^3 GeV, and compared to the predictions from the Bischel theory for the 2 nominal tracker sensor thicknesses and taking into account the mean crossing angle of CRAFT data.

Data points are obtained by computing the MPV of Landau fits in each slice in P, with corrections for zero-suppression and clustering, path length in the silicon, and synchronization effects.

Error bars include the statistical uncertainty from the fit. The shaded bands represent the fully correlated uncertainty from detector effects like the synchronization, the active thickness of sensors, or the charge deficit from zero-suppression, estimated altogether to 1.5%.



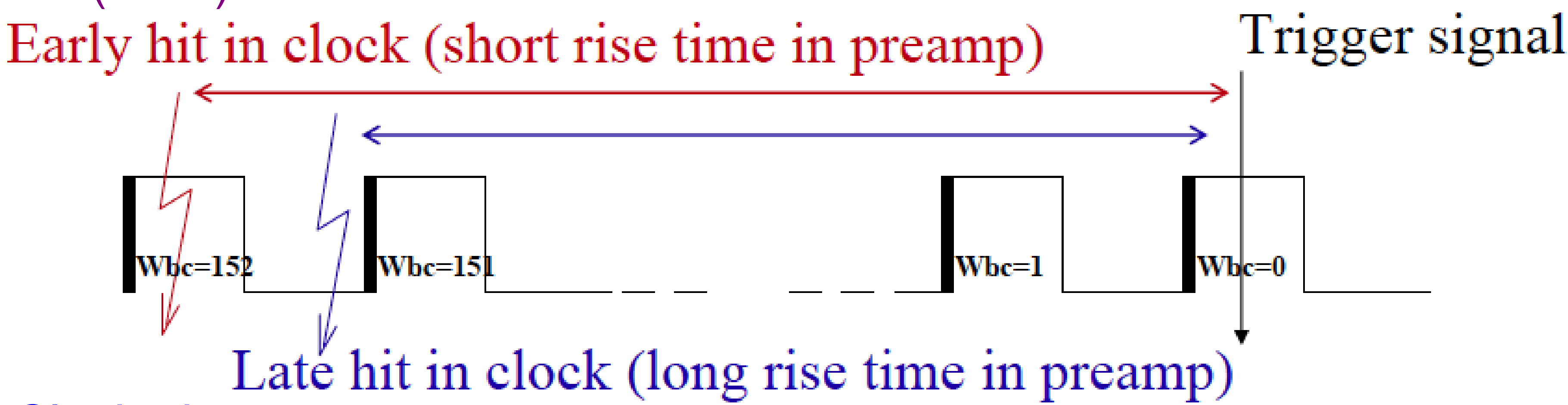


The small dip around 5GeV comes from a contamination by off-time muons wrongly assigned to the bunch-crossing in muon chambers at phi=0 or pi.

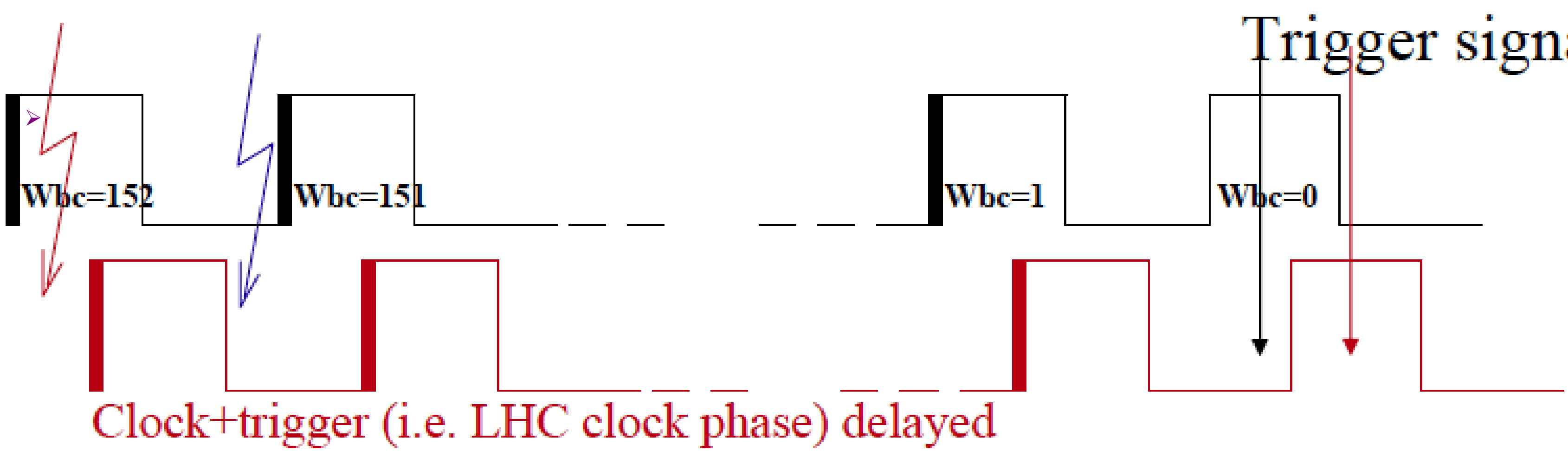
Selection:
* event selection: anti-retriggering filter
* tracks with chi2<10, nhits>4.
* hits made of less than 4 hits

The adjustment of data to the predictions provides an absolute gain calibration of the energy loss: 262 +/- 3 e^-/ADC, fully compatible with the value obtained using the internal pulser in each module (269 e^-/ADC)

- Trigger latency (WBC) scan:
  - Hit stored in ROC with time-stamp in units of bx
  - When trigger signal arrives, hits corresponding to a pre-set time stamps (WBC) are readout

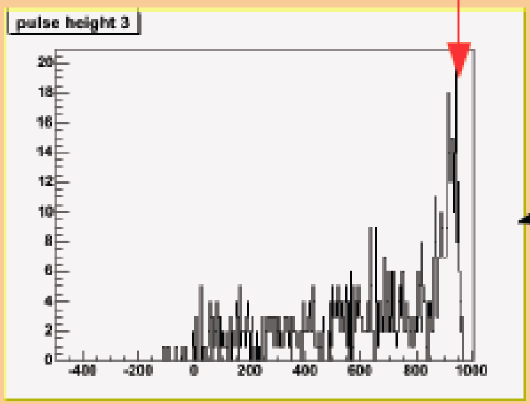


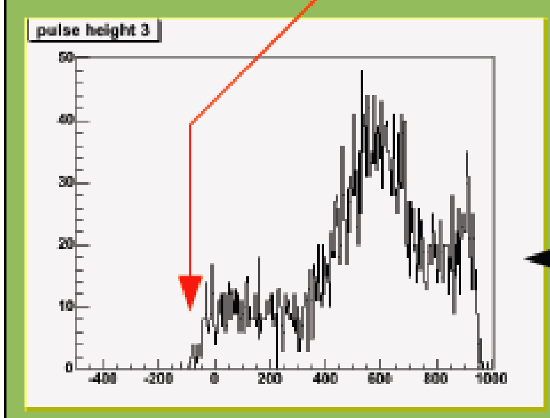
- Clock phase scan:

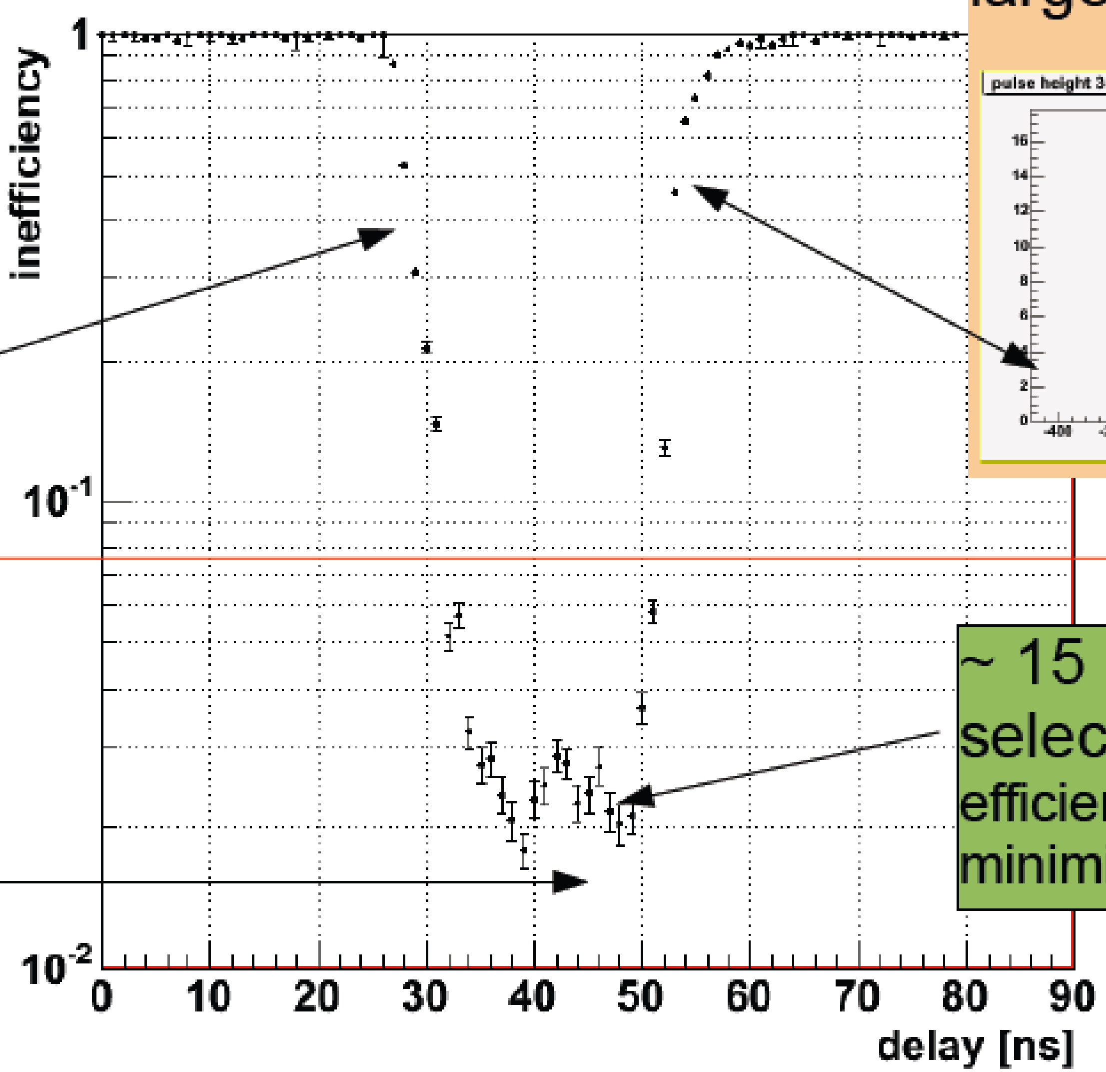


delay scan: vary system clk wrt beam

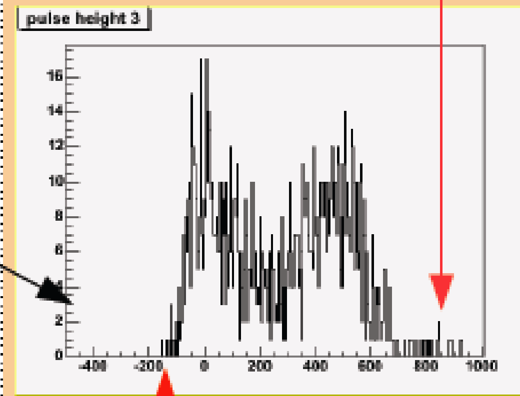
too early, see only large pulses:







too late, loose very large pulses



~ 15 ns plateau
select timing:
efficient for large Q,
minimize loss at low Q